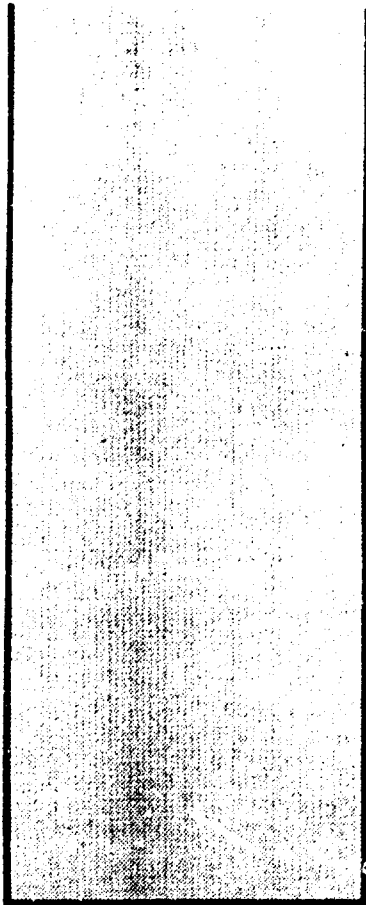


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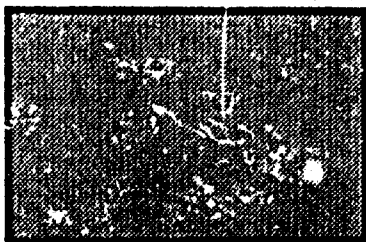
Technical Report 2732.01/40
Prepared for JANAIR



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PICTORIAL DISPLAYS FOR FLIGHT *Code 1*

W. L. CAREL



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HUGHES

DISPLAY SYSTEMS DEPT
HUGHES AIRCRAFT COMPANY
CULVER CITY, CALIFORNIA

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PICTORIAL DISPLAYS FOR FLIGHT

HUGHES AIRCRAFT COMPANY
CULVER CITY, CALIFORNIA

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PICTORIAL DISPLAYS
FOR FLIGHT

W. L. CAREL

Prepared for: JANAIR under
Office of Naval Research
Contract NONR 4468(00)

Prepared by:
Research and Development Division
Hughes Aircraft Company
Culver City, California

December 1965

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This report presents work which was performed under the Joint Army-Navy Aircraft Instrumentation Research (JANAIR) Project, a research and development program directed by the United States Navy, Office of Naval Research. Special guidance is provided to the program for the Army Material Command, the Office of Naval Research and the Bureau of Naval Weapons through an organization known as the JANAIR Committee. The Committee is currently composed of the following representatives:

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The goals of JANAIR are:

- a. The Joint Army-Navy Aircraft Instrumentation Research (JANAIR) project, is a research project, the objective of which is to improve the state of the art of piloted aircraft instrumentation.
- b. The JANAIR Project is to be responsive to specific problems assigned, and shall provide guidance for aircraft instrumentation research and development programs.

- c. The JANAIR Project will conduct feasibility studies and develop concepts in support of service requirements.
- d. These efforts shall result in reports and the knowledge to form the basis for development of improved instrumentation systems, components, and subsystems.

ACKNOWLEDGMENTS

Although the author takes responsibility for the contents of this report, the work accomplished was really conducted by an organization, and several people were called upon for contributions. Dr. S. N. Roscoe wrote the sections on the requirements for and display of wire avoidance information. He also wrote parts of the discussion of HSD functions and the operational use of map displays. Mr. F. K. Schonlau derived the bulk of the detailed requirements for the HSD map displays. The discussion of the various measures of resolution was written by Mr. M. Weihrauch and was based on earlier work done by Mr. H. L. McCord. Dr. R. R. Law wrote the section on display devices. The greater part of the analyses of the sensing and data processing requirements was written by Mr. C. C. French: Navigation Updating, Obstacle and Wire Detection, and Velocity Vector Sensing. Mr. E. P. Hechtman and Mr. S. B. Demkowicz contributed the method for deriving the command velocity vector. The tedious job of compilation was patiently carried out by Mr. F. Rossetti, who also drew the art work. To all of these contributors the author is grateful.

TABLE OF CONTENTS

	Page
ACKNOWLEDGMENTS	v
FOREWORD	1
PICTORIAL DISPLAYS	3
Definition	3
Pictorial Codes	4
Characteristics of Pictorial Displays	6
DERIVATION OF PILOT DISPLAYS	8
Information Requirements	8
Sample Analysis of Pilot's Task	11
Concept of Pilot Task Heirarchy	14
General Characteristics of Vertical Displays	20
General Characteristics of Horizontal Displays	21
Design Rules for Pictorial Displays	22
VERTICAL SITUATION PICTORIAL DISPLAYS	24
Literal Vertical Situation Displays	25
Analog Vertical Situation Displays	41
Skeletal Vertical Situation Displays	53
Control of Velocity Vector	62
Head-up Displays	63

TABLE OF CONTENTS (Continued)

	Page
HORIZONTAL SITUATION PICTORIAL DISPLAYS	70
Display Functions	70
Map Displays	73
Sensor Displays	84
PICTURE QUALITY REQUIREMENTS	103
Brightness and Grey Scale	103
Field Rate	115
Data Rate	120
Measures of Resolution	121
Display Size	136
DISPLAY DEVICES	140
Possible Approaches	140
Preferred Approach	146
Specific Design	148
Areas Requiring Future Work	152
SENSING AND DATA PROCESSING	154
Overview	154
Navigation Updating	163
Obstacle and Wire Detection	178
Velocity Vector Sensing	189
Determination of Command Velocity Vector	195
REFERENCES	203

FOREWORD

This is the final report of a study to examine the potential of raster scan pictorial displays for aircraft application. By mutual agreement with the Office of Naval Research the scope of the effort was restricted to four mission segments for both normal and steep gradient vehicles for one- or two-place aircraft. The mission segments are:

- 1) Take off
- 2) Climb out
- 3) Point to point navigation
- 4) Landing

The program was divided into two phases; 1) The analysis of the potential of pictorial displays and, 2) The definition of the associated sensor and data processing requirements.

The study was conducted with no particular avionics system or aircraft in mind with the result that the report that follows deals with generic problems rather than the tradeoff and design issues specific to a particular system.

Because this is not an exhaustive review of all possible display techniques there is, in a report like this, a cachet of approval for the displays studied even though such displays may be cited as mere examples. In this instance such an approval is explicit -- with the exceptions noted all the displays studied are believed to have merit. However, the reader should know that it has been necessary to make value judgments that are not supported by direct empirical evidence. Every attempt will be made to show what evidence there is to justify or reject such choices, but it must

be acknowledged that the evidence is incomplete as it always will be. The design and evaluation of information displays is, alas, not yet an exact science.

PICTORIAL DISPLAYS

DEFINITION

The color "red" cannot be described; examples of it can only be pointed to. Many words are of this type — words for which it is difficult to find a concise and satisfactory denotative definition. "Pictorial" belongs to this class of words and although the term can be defined to serve the general meaning, the way in which the term will be used in this report can also be defined by connotation and illustration — by pointing.

The most comprehensive definition of pictorial as it applies to visual pictorial codes is that such codes are ways of showing the relations between a great many variables in a common frame of reference by the topology or dynamics of the elements displayed. Schematic wiring diagrams are pictorial codes as is the movie STAGECOACH. The one is abstract and static, the other literal and dynamic. Most of us are familiar with static pictorial codes and the use of such codes enables us to envision how a system works or what it looks like in Cambodia. We can envision this because the code enables us to comprehend simultaneously the relationship between a large number of variables — relationships indicated by the topological arrangement of the elements comprising the code: to the left of, above, inside, following, in front of, etc. Visual pictorial codes employing dynamics are less familiar although complete movies have been made with totally abstract figures where the meaning of the movie was derived solely from the motions of the figures in relation to each other. In the laboratory it has been shown that considerable information of a specific type is transmitted simply by manipulation of the temporal relations between moving abstract figures. This point has been belabored because in the utilization of pictorial displays for flight, the

importance of display dynamics in the portrayal of dynamic events cannot be too strongly emphasized.

PICTORIAL CODES

The design of pictorial codes for use in flight has as its object the creation of the appropriate microcosm in the cockpit. Manufactured information sources such as displays are substitutes for the direct sensing of environmental events, and an objective in the design of such substitutes is to represent the environmental events so that little or no misinterpretation of the action environment may be made by the observer. The action environment comprises those dimensions that affect the decisions required of the operator. When that environment is represented by a pictorial code, the implication is that the observer may easily recognize the referent state or object when looking at its representation.

A visual pictorial display is the result of the mapping of certain characteristics of the reference space to the space of the display by a simple transform. Therefore, such displays usually retain the topological relations of the reference space or model and the extent to which they maintain precise geometric congruence — albeit with a change of scale — is the extent to which the display maintains fidelity. Map displays are projections of certain characteristics of the earth's surface plus some conventions describable in the same coordinate system. The contact analog display is the perspective transform from a three-dimensional model to the display face. Tracking displays are maps of some selected characteristics of the control system mapped from the control to the plane of the display. Pictorial means a one-to-one correspondence between the display and reference domains with no differential transforms along a given axis.

There are degrees of realism in pictorial representation; a stereo full color photograph is highly literal whereas the map is a severe, although conventional, abstraction.

Most maps do not look like the world we see around us but they do look somewhat like the conceptual pictures we carry in our heads for the perfectly good reason that those concepts were formed by looking at maps.

Geographical concepts and maps do not copy the physical environment. Such concepts are true to the behavioral environment rather than the physical environment. There is of course a geometric similarity between these two environments, but maps are abstractions of those properties of the physical environments useful for behavior, e. g. , orientation, and the like.

Visual pictorial codes, then, must represent the behaviorally relevant characteristics of the environment or referent. It is curious to note that the referent need not be a visible or even a real object; it may be a conceptual scheme or an imaginary thing. Models of the atom and pictures of Mickey Mouse are both pictorial representations that may have no physical or at most a conceptual existence. In the design of pictorial codes, the object is not to make them as realistic as possible — in the sense of making literal copies of the physical environment — but to make them structurally similar to the referent. Dimensions should not be transformed, and distortions are permissible only if they enhance recognition or operational effectiveness.

The choice between symbolic and pictorial codes for flight application depends on the kinds of decisions required of the operator. As the pictorial code integrates a great deal of information in a common frame of reference, its use is indicated where the required decisions are based on an understanding of the relations between data. If, on the other hand, a decision requires precise readout of a single dimension then a symbolic code is appropriate. A digital voltmeter employs such a code.

Consider the case of a commercial aircraft confronted with an emergency that requires landing. Before deciding how, when and where to land, the pilot must consider a host of variables: present position, airport locations, runway length, fuel load, economics, risk, etc. Many of these variables can be represented on a pictorial map display and, in this particular instance, the display represents a library of contingent information that is accessible as the need arises. To design a display as a potential source of information allows the operator a flexibility in operation that is difficult to achieve with highly programmed data. It is difficult to imagine that precisely the same information could be utilized as rapidly using alpha-numeric

displays. A second effect of multiplying information is that the uncertainty about what is actually happening is reduced, and the likelihood of the operator selecting the correct action is increased.

CHARACTERISTICS OF PICTORIAL DISPLAYS

Displays that present a large number of variables in a coherent frame of reference also enhance the ability of the operator to detect a failure or error in the display system itself. Characteristically, pictorial displays deal with highly redundant and correlated information, and it is this feature which permits rapid error detection. In a cockpit with standard flight instruments, it is sometimes the case that one of the gauges is suspected of malfunctioning. If the gyro-horizon indicates a left bank and the compass indicates a turn to the right, the pilot can decide which is correct by consulting other instruments or by estimates of the probable reliability of each of the candidate culprits. In this sense the instruments are being used not so much for control as they are for diagnosis. In order to make any sort of diagnosis, the pilot needs either redundant information or a thorough knowledge of the reliability of the suspected instruments. That such diagnoses present the pilot with a dilemma can be seen from the number of incidents where an airline pilot will make an unscheduled landing because a warning light has illuminated, and he has no way of knowing whether the defect lies in the warning system or the referent system. Because the penalty for a wrong diagnosis may be fatal, he lands. In integrated displays, the simple recognition of a discrepancy may be quickly noted. For example, when using the contact analog display if the bank angle is not correlated with turn rate and direction, this fact is detected immediately. To decide, however, whether the bank channel or the heading channel is in error depends on precisely the same kind of redundant information or reliability history that operates with any instrument system whether symbolic or pictorial. In this particular instance what the pictorial display promises is rapid error detection and ease in correlating similar information.

A general property of pictorial displays is that because they characteristically use many dimensions rather than steps within a dimension to convey information they take advantage of a human property; a human can

process more information by the addition of perceptual dimensions than by increasing the discriminability along a dimension. Related to this is the fact that, because the information portrayed by the dimensions is inherently related, the observer doesn't have to change "set" when going from one class of information to another. Because such codes are based on highly developed population stereotypes or on the psychophysical and cognitive properties of man, they are easily learned. In summary, pictorial codes are easily learned, provide operational flexibility, and enhance failure detection and diagnosis.

DERIVATION OF PILOT DISPLAYS

INFORMATION REQUIREMENTS

In order to understand whether or not pictorial displays are applicable to the problems of flight, one must first create a concept of the pilot's job. The problem is not usually phrased this way for according to conventional dogma the way to determine the applicability of pictorial or any other coding technique for flight operations is to assay the worth of the code against pilot information requirements.* The information requirements are determined by examining, in turn, the mission requirements, the system functions, the crew functions, performance criteria, and the information the crew needs in order to carry out their assigned functions.

We have cut short this procedural ritual by using representative lists of pilot information requirements that already exist. Funded analyses to yield pilot information requirements have been made for many systems over the course of the past few years, and the outputs of some representative analyses were examined with the object of determining whether or not a

*In actual avionics systems work the choice of display design characteristics often depends not on formal analysis but on:

- 1) Familiarity with the system — with few exceptions, pilots and ex-pilots make the most significant contributions to the design of aircraft instrument displays.
- 2) Panel space.
- 3) Engineering feasibility and available hardware.
- 4) User acceptance.

Design is followed up, of course, by iterative evaluations whether they be paper, simulation, or flight test. It is here that formal error and other forms of analysis are called for.

consensus could be reached on pilot information requirements. Lists which purport to be pilot information requirements for landing as they appear in four different reports are shown in Table I. While each of these lists, admittedly, is derived from analysis of a different system, it can be seen that there is marked difference of opinion among these expert authors, differences revealed not so much by contradiction as by omission of items.

When confronted with four such lists, what does one do? There is indeed a minor commonality among these lists, but to extract these common elements and use the least common denominator as the basic items of information seems a blind and imprecise procedure. In fact none of these lists, nor all of them taken together, is an exhaustive statement of the pilot's information requirements for much of the information the pilot requires is obtained through training and is never explicitly displayed in the cockpit. The output of most studies of pilot information requirements is not a total description of pilot information requirements but is a list of information presented by current or proposed instruments or a selection of those parameters that should be displayed in the cockpit for a given system according to the judgment of the investigator. The lists shown in the table obviously deal with partial requirements and are constrained by assumptions about instrumentation available, the nature of the pilot's task, etc.

One may conclude that lists of pilot information requirements as they exist are almost useless as a basis for deciding what information to include in pictorial displays for the pilot. Furthermore it can be argued that even if the information requirements for the pilot were exhaustively known and the required performance for each displayed variable specified numerically, a creative leap is still required to vault the gap between those requirements and the best way of encoding the information. There is no logical or necessary connection between these lists of information requirements and methods of encoding the information.

The main reason that the connection between information requirements and methods of encoding remains obscure is that the information requirements often consist of lists that imply no necessary relation between items

TABLE I. REPRESENTATIVE LISTS OF PILOT INFORMATION REQUIREMENTS

LIST NO. 1	LIST NO. 2	LIST NO. 3	LIST NO. 4
<p>PITCH ROLL HEADING AIRSPEED GROUND SPEED RATE OF CLIMB ALTITUDE CHECKPOINTS AIRCRAFT POSITION (MISS. REF.) AIRCRAFT POSITION (GEO. REF.) COMMAND VELOCITY COMMAND ACCEL. COMMAND ALTITUDE COMMAND HEADING SLANT RANGE TO OBJECTIVE THROTTLE PRESS. MANIFOLD PRESS. THRUST MANIFOLD TEMP RPM ELEC. POWER HYDR. PRESS AUTOPILOT CANOPY TRIM FUEL QUANT. FUEL FLOW RATE LAND GEAR DRAG CHUT. AIR BRAKE PANEL INDICATORS VOICE COMMUNIC. DATA LINK OIL PRESS. ENG. TEMP ILS, TACAN ETC TIME WIND VELOC. WIND DIRECTION TOPOGRAPHIC OBSTRUCTION WEATHER OR AIR DEFENSE LOCATION NUMBER OTHER AIRCRAFT LOCATION OTHER AIRCRAFT</p>	<p>PITCH ROLL HEADING AIRSPEED GROUND SPEED RATE OF CLIMB ALTITUDE COMMAND BANK ANGLE COMMAND PITCH ANGLE ROLL ANGLE - CARRIER DECK ROLL ANGLE - CARRIER DECK PREDICTED PITCH ANGLE - CARRIER DECK PITCH ANGLE - CARRIER DECK PREDICTED COMMAND HEADING CARRIER HEADING (EARTH REF.) CARRIER HEADING (LOC. REF.) CARRIER HEADING (EARTH REF. PREDICTED) TRACK COMMAND TRACK A/C POSITION A/C POSITION COMMAND CARRIER POSITION CARRIER POSITION PREDICTED FIX POINTS (LOC. REF.) FIX POINTS (LOC. REF. PREDICTED) DANGEROUS WEATHER (LOC. REF.) FIXED OBSTACLES (LOC. REF.) FRIENDLY A/C (LOC. REF.) UNFRIENDLY A/C (LOC. REF.) ANTICOLLISION BREAKPOINT (LOC. REF.) COMMAND ALTITUDE BASE ALTITUDE FIX POINT ALTITUDE RUNWAY ALTITUDE TURBULENCE ALTITUDE OBSTACLE ALTITUDE (LOC. REF.) OTHER A/C ALTITUDE (LOC. REF.) OTHER A/C ALTITUDE (LOC. REF. PREDICTED) RATE OF CLIMB COMMAND CARRIER DECK HEAVE CARRIER DECK HEAVE PREDICTED RATE OF TURN RATE OF TURN COMMAND AIRSPEED COMMAND CLOSURE RATE W/ A/C CLOSURE RATE W/ A/C COMMAND CLOSURE RATE W/ CARRIER COMMAND CLOSURE RATE W/ CARRIER CENTER CLOSURE RATE TO STORM CENTER WHEEL POSITION FLAP POSITION (BEST & PRESENT) TRIM CONDITION (BEST & PRESENT) CONTROL GAIN (BEST & PRESENT) SPEED BRAKE V-G FUEL (PRESENT, PREDICTED, DISTRIBUTION) ENDURANCE TTG TO CUT LENGTH & WIDTH OF RUNWAY LANDING ROLL (W/PRESENT F.T.A. AT LIGHTEST WEIGHT) PATH MADE GOOD - OWN SHIP PATH MADE GOOD - OWN SHIP PREDICTED PATH MADE GOOD - MOVING BASE PATH MADE GOOD - MOVING BASE PREDICTED PATH MADE GOOD - OTHER A/C (PAST - PREDICTED) PATH MADE GOOD - STORM CENTER (PAST - PREDICTED) PATH TO BE MADE GOOD - OWN SHIP PATH TO BE MADE GOOD - SURFACE OBJECTS PATH TO BE MADE GOOD - OTHER A/C</p>	<p>PITCH ROLL HEADING TAS STEERING COMMANDS AIRCRAFT POSITION & COURSE ALTITUDE ANGLE OF ATTACK LOCATION OF CARRIER LOCATION ALTERNATES FUEL RANGE COMMAND HEADING SPEED CMD. SPEED CMD. ALTITUDE GUIDE SLOPE LOCALIZER</p>	<p>PITCH ROLL TRIM PITCH IAS & TAS CMD. BARO. ALTITUDE RADAR ALTITUDE ALTITUDE ANGLE OF ATTACK CMD. TAS STEERING COMMAND MINIMUM RANGE WARNING STATION KEEPING TIME TO GO WAVE OFF</p>

of information. In fact such lists discourage the consideration of the information requirements as an organic system to serve a complex of necessarily related crew functions.

Sample Analysis of Pilot's Task

An alternative approach to determine the applicability of pictorial display is to examine the pilot's job in the context of current or near future systems. To this end, a partial analysis of the pilot's job in the approach and landing to a carrier while using a data link was conducted. The mission segment chosen is schematized in Figure 1. The aircraft starts about 10 miles aft of the carrier, intercepts the ACL gate at about 4 miles, and proceeds to land on the carrier. The aircraft was presumed to be under data link control using control messages 4, 5, and 6. In the diagram, discrete messages are shown below the line and control messages above. Although the sequence of discrettes may not be precisely as shown, one may, using this information, construct a rough diagram which illustrates the tasks of the pilot as they cluster around use of the data link information. Such a diagram is shown in Figure 2. It is evident that much of the data link information the pilot must deal with does not lend itself to pictorial display -- all the discrettes are in fact displayed as legends. It is equally apparent that the pilot is being tightly controlled by the ground through the data link and that no provision has been made to provide the pilot with position and traffic information that would enable him to make his own decisions about altitude, speed, and the like or would permit him to evaluate the likelihood that the data link commands are correct.

Although the pilot may not relish working in such an impoverished information environment, it cannot be denied that pilots may operate successfully with such systems for the required information is still in the system albeit it is now on the ground. In systems employing tight ground control the need for a complex pictorial display in the cockpit is seldom realized, for the pilot is relegated to the role of a servomechanism, and in that role he is characteristically supplied only with lower loop commands. It is his function merely to null errors. This philosophy of operation contradicts what we

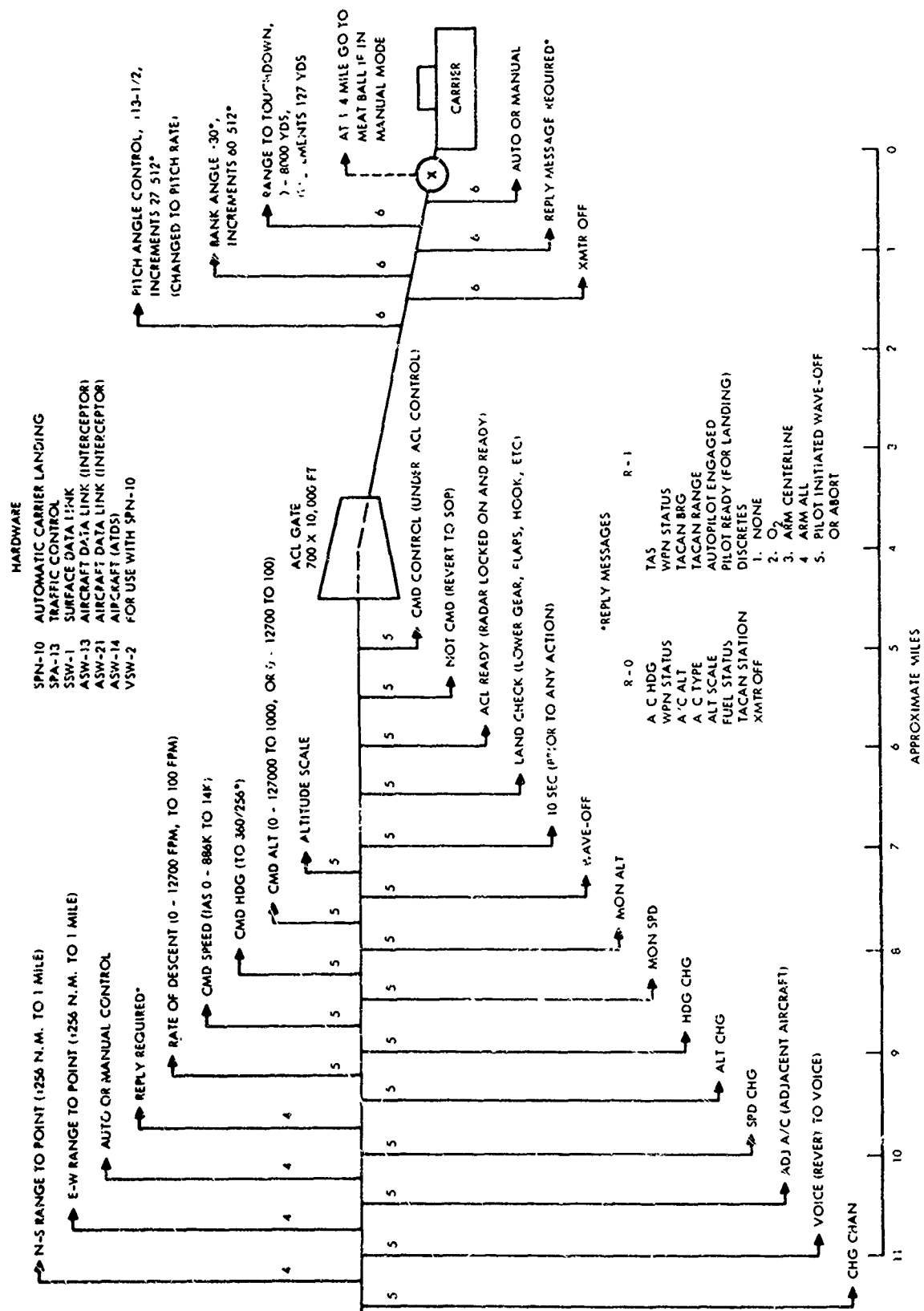


Figure 1. Data Link Messages for Approach and Landing

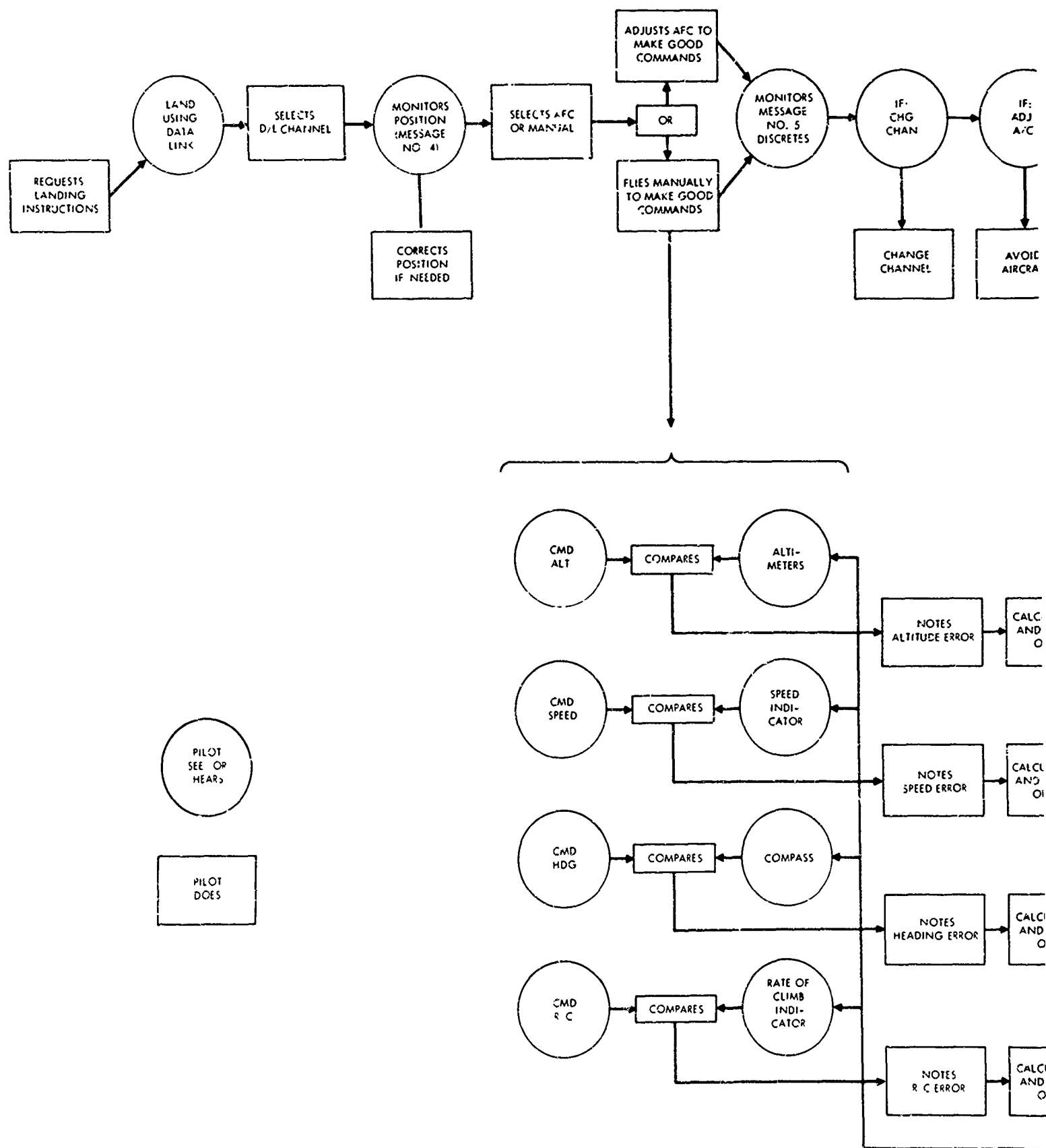
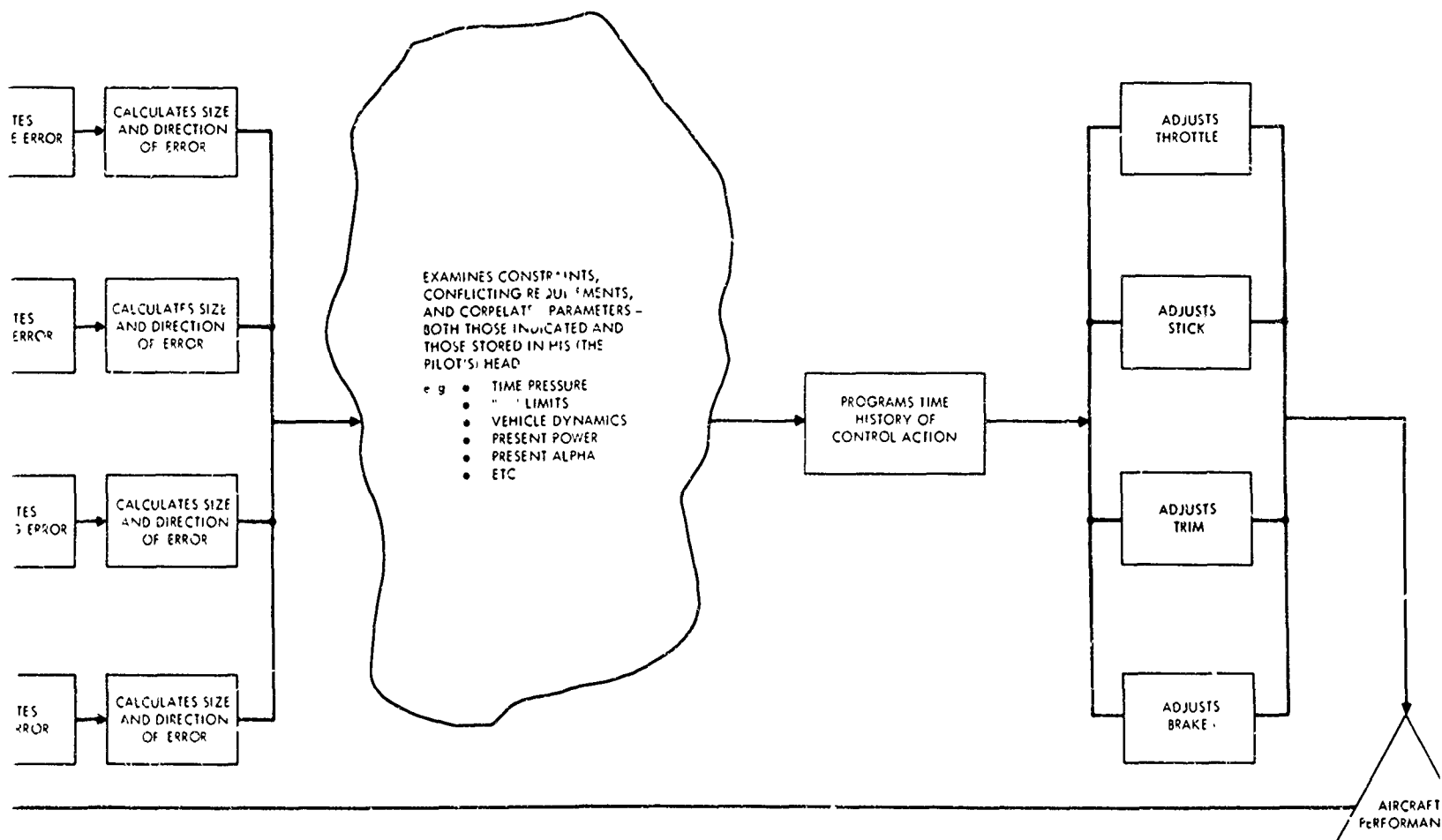
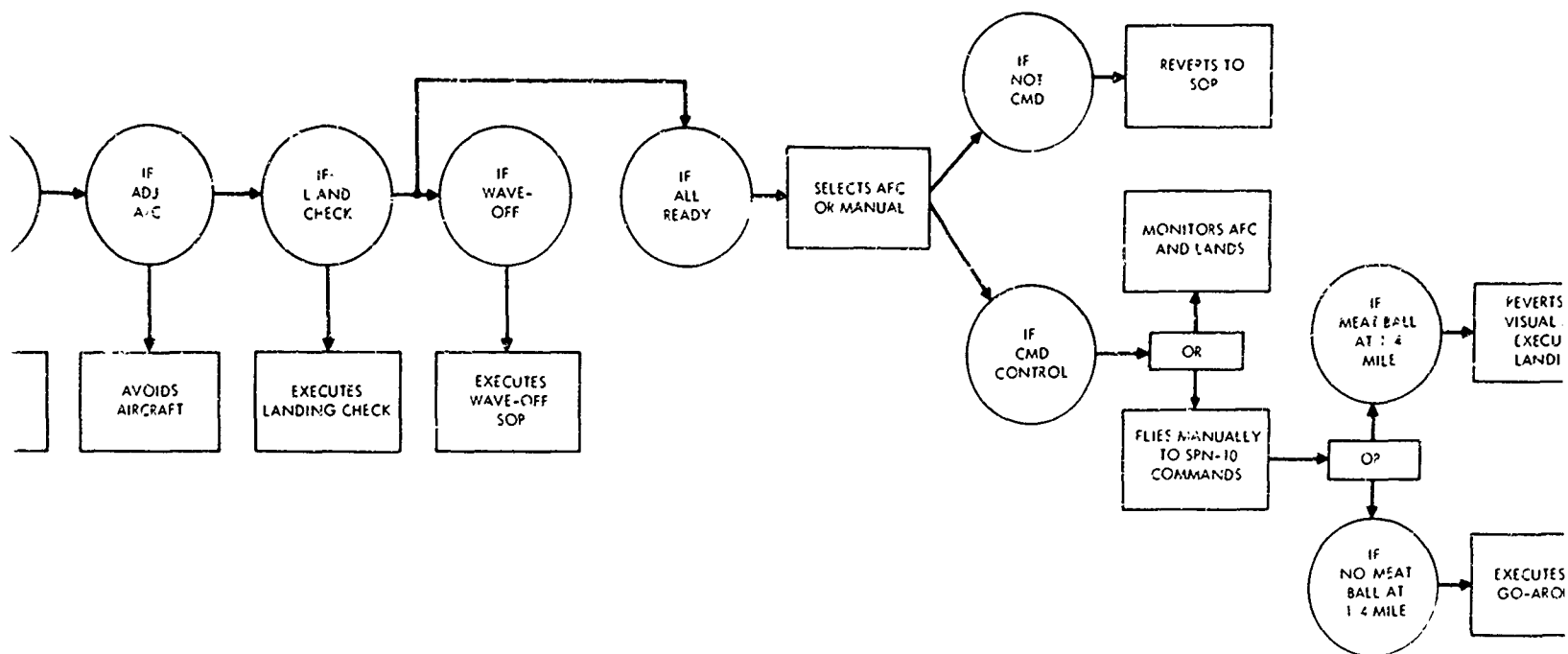


Figure 2. Representative Pilot Tasks i

A



ot Tasks in Landing While Using Data Link



between a way of structuring the pilot's job and pictorial displays. This relationship provides the rationale for the choice of pictorial displays and will be elucidated in the following paragraphs.

With no intention of writing a treatise on guidance we shall outline the broad functions of a vehicle guidance and control system in order to provide a starting point for discussion of the pilot's overall guidance and control task. The development and operational use of a vehicle guidance and control system implies the following:

- 1) the selection of a goal (for example, a ground target or destination)
- 2) the measurement of the position of the vehicle relative to the goal
- 3) the selection of a path to the goal consistent with vehicle constraints
- 4) the measurement of path error or the computation of predicted error at the terminal goal given present performance
- 5) the selection and use of sensing and control mechanisms to physically realize a control law and thus reduce the error or make good the path
- 6) the selection of components for the synthesis of the sensing and control mechanisms
- 7) the selection of material for the required components

In completely automatic vehicle systems, all of these steps are carried out either directly or implicitly by the design team. In symbiotic systems containing men and machines, some of these steps are left to the operational crew. The type of information and displays needed by the crew will depend heavily, of course, on which of these functions they carry out.

In primitive aircraft the designer implemented step 7 and parts of steps 5 and 6. The pilot was coupled to the air foils by a simple linkage, and he acted as the primary sensing, measuring, computing, and control power device. The end goal may have been selected by his superiors, but

the pilot did all else. In those early aircraft the instrumentation was simple — the pilot obtained much of his information from the outside world. As aircraft became more sophisticated and their missions more demanding, the pilot had to depend more and more on artificial devices for sensing, control, and the display of information about aircraft performance but even in modern aircraft the pilot has to translate the long term goal objectives which are typically expressed in terms of time and space into instantaneous objectives for each individual instrument which are typically needle positions. In order to relate the space-time requirements of the eventual goal to each of these instrument sub-goals he must understand completely the dynamic relations between aircraft performance, instrument response, and control action.

The linking of the chain of mental and motor events that enables the pilot to select an appropriate control act in order to bring the aircraft closer to the final goal constitutes the overall task of the pilot, and it is the discovery and mastery of the relationships between subtasks within this chain that makes flight both interesting and difficult. To make the relationship between these subtasks more explicit should be the intent of any sophisticated display system, and in order to do this the relationships among these tasks must be teased out.

For the pilot, the major task clusters within the overall task deal with four general questions.

- 1) where in the world am I with respect to my end goal?
- 2) what is and what should be my velocity vector?
- 3) what is and should be my attitude and/or angle of attack?
- 4) what should I do with the controls?

These questions constitute categories of information, and for each of these categories there is a desirable state of affairs at some particular time, i. e. there are goals for each of these categories. In principle the pilot could be commanded directly with respect to each of these goals separately. By way of audio or visual displays he could have his terminal goal defined for

him, be told what path to take, what attitude to assume, or be informed how, when, and where to move the control stick.

The categories however are not independent but are inherently related because of the way the aircraft operates. They are in fact related in a hierarchical fashion and the pilot's overall job is therefore comprised of a hierarchical series of tasks in which he is required to realize a goal at one level of the hierarchy by programming a set of sub-goals for the task at the next subordinate level in the hierarchy. Figure 3 is a diagram illustrating this concept and is intended to show that the pilot's tasks are interrelated in a hierarchical fashion and that the higher order loops impose a forcing function on the subordinate loops. Each of these loops can be considered as a closed loop system, and all too often only the closed loop aspect of the pilot's job for each loop taken separately is considered. The consequence is that we have tracking displays that deal with loop 4, attitude displays that deal with loop 3, navigation displays that deal with loop 2, etc. The fact that the information required in adjacent loops is related is seldom taken into account in display design, and the way the subordinate variables affect the attainment of the next superior set of goals is not often displayed.

The operational disadvantage of considering each of these loops separately is that such a procedure may not take advantage of the flexibility and adaptability of the human crew. In general man's behavior is goal directed, and he will adopt any of a number of paths to reach a goal. Systems that exhibit a fixed goal or constant output through adaptation are called self-regulating, homeostatic, etc. The hallmark of such systems is the adaptation of the system to changing conditions to achieve a steady state or reach a criterion objective.

When using the tools and implements he invents, man continues to exhibit adaptable and goal-directed behavior. At times, to reach highly desirable goals, he surpasses the intentions of the tool designer. He may use a screw driver to open a beer can. Tools — and aircraft systems are tools — can be thought of as simply extensions of the man's body and intellect: as amplifiers for his physical strength, sensory range, or data processing

capability. A man-machine complex, then, will exhibit the same behavioral properties as man; that is, goal direction and path alternation. Of course, this will only apply in systems where there is more than one way of achieving the goal. If the possibility of alternate solutions does not exist because there is a unique solution, then the addition of man to the system will yield no benefit with regard to adaptability.

Even if each loop is displayed separately the pilot will exhibit the human property of adaptability. Each such individual display may define a sub-goal for the pilot but the adaptability he exhibits will only be that necessary to reach the particular sub-goal represented in the display.

Taken separately the display of each of these types of information alone will have certain operational and procedural consequences. With a steering signal display the only decision the pilot has to make is where, when, and how to move the control. The only adaptability he may show is to adopt a transfer function to minimize his mean square tracking error, and so forth. If one relied on a steering signal display alone one could accept a very low skill level for with a properly designed tracking display employing quickening, highly precise correct control responses can be learned by a naive operator in a matter of minutes. Of course, such a display taken alone leads to cognitive blindness in the sense that the operator has no idea what the aircraft is doing.

A map display showing the terminal goal is more like a potential source of information where the information extracted will depend on the operational demands. The proper use of these displays demands a greater range of intellectual skills, but the consequence is a greater potential for adaptable behavior with the characteristic opportunity for great brilliance or alarming stupidity.

The kinds of pilot behavior demanded by each of these loops also differs markedly. It can be seen that as one progresses down the hierarchical structure, the pilot tasks require increasing degrees of psycho-motor involvement. The pilot decisions based on the map display at the highest

level in the hierarchy are almost solely cognitive, but the "decisions" based on the tracking display at the lowest level are almost solely psycho-motor. This means that the importance of display dynamics grows larger the nearer one approaches the lowest loop whereas at the higher loops more dimensions are handled, and the code topology is more important. Conceived in this fashion a tracking display may also be pictorial, and what it portrays is the dynamic relationship between the control and the error of some controlled element.

In summary, increasing control precision is gained as one displays information in the lower loops. Increasing tactical adaptability is gained by presenting information in the higher loops. It is desirable that the eventual system exploit the merits of each of these information classes. This may be achieved in a single integrated pictorial display because the information classes are not discrete but are related by the hierarchical structure.

The ideal display system would show the relationships among all the important variables at all levels in the pilot's task hierarchy simultaneously. This was stated in a slightly different way by Williams (1947) who said, "The best form a sub-goal can take is the direct display of the aircraft, the terminal goal, and the physical facts on the same perceptual continuum as is the case, for example, in contact flight when the goal is in sight." Such a conceptual ideal is not capable of physical realization because the required range and resolution of the displayed variables at all levels in the hierarchy are such as to prevent simultaneous display. For these practical reasons displays are characteristically divided into two types; flight control displays and navigation displays or, as they are sometimes called, the vertical and the horizontal displays.

GENERAL CHARACTERISTICS OF VERTICAL DISPLAYS

The forward-looking vertical displays used for flight control are nominal azimuth-elevation displays, and to keep a common frame of reference all variables shown on the display should be capable of expression in az-el terms. Pictorial flight control displays present information from the "forward" view and represent dimensions that can be meaningfully portrayed in the Y-Z

plane of the aircraft: pitch, roll, heading, angle of attack, glide slope error, carrier az-el, steering error, and the like. They are commonly called vertical situation displays (VSD) but usually deal with problems of flight control.

Because such displays are concerned heavily with tracking behavior the important variables are, in addition to content and symbology, element dynamics and sensitivity. The use of quickening and short-term prediction is thereby indicated.

One might call the information displayed thereon information about the present space, for the display will represent objects that are local and parameters that change rapidly with time. It will be design policy to represent as many levels of the pilot's task hierarchy as possible without destroying comprehension or simple legibility. For this reason, wherever possible the display will represent simultaneously the terminal goal, the path to the goal, aircraft attitude and flight path information, and steering commands.

A display based on this design policy will allow the pilot either to direct or monitor the activities of the system as parameters low in the hierarchy are controlled in terms of the progress being made towards goals specified in the higher order loops. Wherever possible and useful, prediction of the consequence of lower loop behavior in terms of attainment of higher order goals will be displayed. Most of the pilot's training is concerned with learning how to make such predictions, and if they could be made explicit on the display, the difficulties of flight would certainly be reduced. Thus, the flight path in the contact analog display which is normally conceived as a command path could equally well be used as an indicator of predicted flight path so that if the terminal goal is represented — an airstrip — the flight path used as a predictor would show the consequence of control action in terms of interception of the airstrip.

GENERAL CHARACTERISTICS OF HORIZONTAL DISPLAYS

The downward-looking horizontal displays are usually plan position indicators at a scale useful for navigation or geographic orientation. Here

again the rule is to maintain a consistent frame of reference and at the same time represent as many levels in the pilot's task hierarchy as may be compatible without confusion. To represent the required information pictorially implies only that the topology that obtains in the real world (or sometimes the conceptual world) is maintained in the display.

The increasing use of the highly versatile cathode ray tube in the cockpit permits the use of the HSD for many tasks other than navigation during different phases of the mission. This display can be used to show raw radar data, IR data, a picture or a map, a variety of symbols, a set of verbal instructions, or a mixture of several types of information depending on the particular mission phase.

DESIGN RULES FOR PICTORIAL DISPLAYS

Integrated displays imply merely that all display elements answer to the same laws and follow the same rules. More is implied in pictorial displays: elements not only follow the same rules but the information displayed must necessarily have a spatial character. While it is true that "pictorial" in the larger sense connotes a sensory similarity between an event and its representation -- the sound of a phonograph recording is a "pictorial display" of an acoustic event -- the discussion in this report refers only to visual representations. The design of pictorial displays for flight then, must be bounded by representations of the spatial parameters important for the hierarchical tasks of flight.

Whether topological or dynamic relations are portrayed, the trick in the design of visual pictorial codes is to remove unnecessary visual structure by "skeletonizing" the information using abstraction but not delete so much visual articulation that the relationship between displayed elements is obscure. The natural physical world is very "noisy" in terms of information useful for any given task, and the display designer attempts to remove the noise without removing the signal. For predominantly topological displays this means altering the content, number of dimensions, or steps within a dimension. For dynamic displays it means altering the time characteristics and scale of the movement relations between control and the display of controlled element error.

These two notions, the notion of a task hierarchy and the notion of spatial pictorial representations, constitute the grounds for conceiving and selecting those displays having to do with flight control and navigation.

VERTICAL SITUATION PICTORIAL DISPLAYS

The candidate vertical pictorial displays -- those that use an azimuth-elevation coordinate system -- fall on a continuum of literalness. We have isolated three classes along this continuum, have named them arbitrarily, and can illustrate them best by example. Type I displays may be called literal and are exemplified by ordinary closed loop T. V. systems. The displays are literal pictures of the real world, albeit they may lack color and binocular visual cues. Type II displays are analog displays like those generated by the Norden and General Electric "contact analog" computers. They are accurate perspective pictures of a three dimensional model, and the dynamic response of the pictured elements is analogous to that which obtains in the visual world of contact flight. Type III displays are skeletal like those used by Sperry in their head-up displays. The display is still pictorial but the content is minimal and made up of fragments, e. g., the horizon line, a representation of the runway, etc.

These three types of displays may all be called pictorial on two grounds. First, geometric similarity between the elements in the display and the structure of the contact visual environment. Second, the motion of the displayed elements is similar to that of their real world correlates. These types differ in the amount of visual realism they contain with the literal display at one end of the continuum and the skeletal at the other. All have been proposed as flight displays for landing operations; all are in various stages of development; none is in operational aircraft.

THE LITERAL VERTICAL SITUATION DISPLAY

Consider a vertical, pictorial, raster scan display to be used for approach and landing. The advantage of the raster scan CRT display is that one can paint many symbols upon it and not be held to the few elemental lines, pointers, and indices characteristic of conventional instruments. For landing, a presumed advantage of this pictorial raster display is that the landing strip or pad can be shown in an easily comprehended relationship to other significant features. When mixed with other more conventional symbols such an arrangement affords the pilot the opportunity of cross-checking instantaneous control commands or position errors with reference, for example, to a glide slope in terms of the terminal goal of the aircraft. The conditions under which a raster display might show to advantage will be the goal of this analysis. We shall deal first with the potential of a literal display.

Experimental Evaluation of Periscope Displays

The most literal displays that have been tried for landing are those obtained by periscope. Two separate studies are reported in the literature: Roscoe (1952); Campbell (1955). The study of Roscoe was one in a series of experiments using a projection periscope mounted in a Cessna T-50. The periscope was pointed dead ahead (a vertical display). What the pilot saw was the forward view on an 8-inch square ground glass screen. At the eye the screen subtended a monocular visual angle of 30 degrees. A series of lenses allowed the experimenter to change the outside angle represented to 15, 25, or 35 degrees which correspond to magnifications of 2.00, 1.20, and 0.86. It was concluded that pilots could land using such a device if design parameters were correctly chosen. Of interest to this discussion is a quotation from Roscoe:

"While safe take-offs and landings were made by periscope under all experimental conditions, the accuracy of the landings both in terms of constant and variable errors, was significantly influenced by the image magnification being employed. The mean point of touchdown for periscope landings

was found to be an inverse linear function of image magnification, the optimal magnification being the one that resulted in the correct apparent distance of objects viewed through the periscope. Variable errors in point of touchdown, as well as constant errors, were increased as a result of departures in either direction from this optimum magnification factor."

The optimum magnification tested by Roscoe was 1.2. An example of the data obtained in Roscoe's study are shown in Figures 4 and 5. The data show that, with respect to variability, periscope performance was equivalent to contact landing at the end of the experimental series. This suggests that the subjects had just learned to respond to some invariant property of the display in a consistent way by the end of the experiment. Had the experiment continued, the pilot probably could have adapted to the distorted worlds of magnification 0.86 and 2.00 and removed the bias so that their mean error would approximate that of contact landing. How long this process would take is unknown and of course it would be hindered each time the pilot made a landing with normal contact vision. We have placed emphasis on the implications of this study because it deals with magnification and magnification is a display characteristic that will differentially affect the optimum design of the three types of pictorial displays; literal, analog, and skeletal. Our premise is that the more realism in the display the more one must recommend a magnification close to unity, or more precisely, 1.2.

In a similar study using a highly realistic literal display, Campbell, et al mounted a binocular periscope for a prone pilot in a B-17 and investigated pilot performance during approach and landing. The outside world was viewed directly, as in binoculars, instead of being projected on a viewing screen as in Roscoe's study. The authors conclude that approach and landing may be accomplished using such a device even though the number of touchdowns attempted by the experimental subjects were few. This pilot conservatism was attributed to their lack of experience with and confidence in the unfamiliar periscope system. Of interest is the fact that the field of view was 70 degrees on all axes and even this was considered too small to

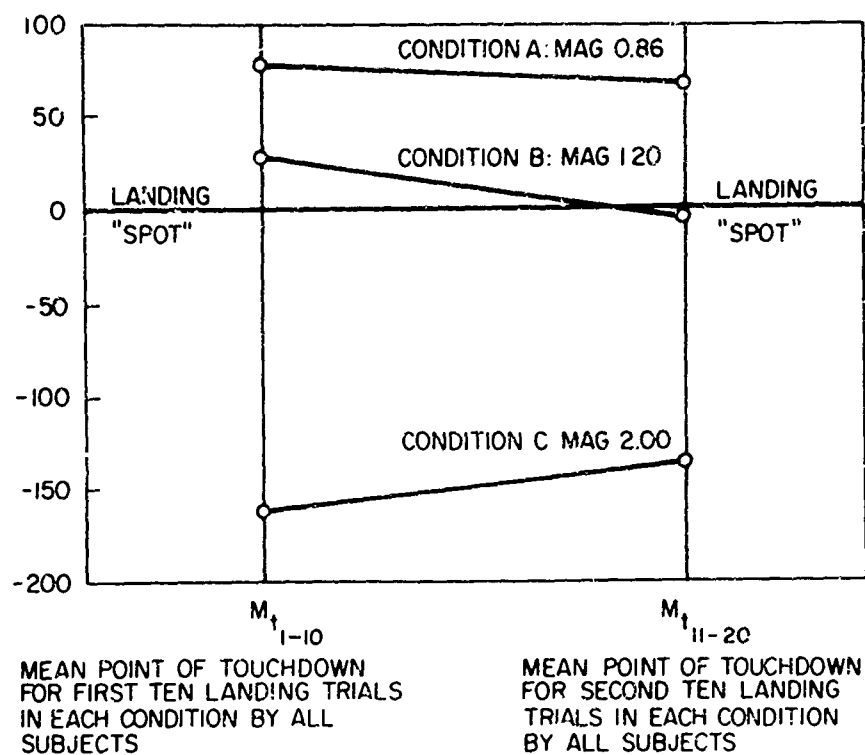


Figure 4. Pilot Performance With Periscope, Average

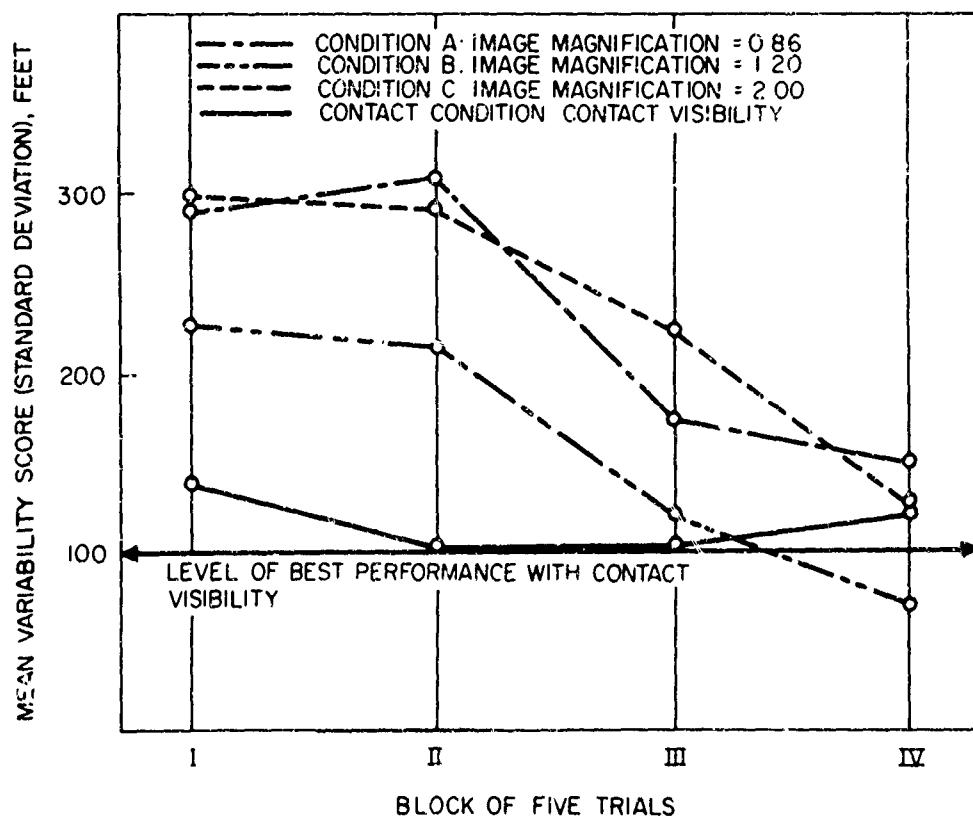


Figure 5. Pilot Performance with Periscope, Variability

adequately fly the then existing traffic pattern. There was also general agreement that with a one power magnification, the apparent magnification is 0.8 if the scan is centered about the flight axis. In other words, to make things look normal a magnification of about 1.2 is required — a finding similar to that reported in Roscoe's study.

Experimental Evaluation of Television Displays

A slightly less realistic display was tested by Bell Helicopter Co. (Elam, 1964) as part of the JANAIR effort. A closed loop TV system was installed in a helicopter. The system was such that the lens covered an outside angle of 22 by 28 degrees that was displayed on a 5.25 by 7.25 inch display. The format of the camera vidicon was apparently different from the format of the display tube so that under the study conditions the magnifications were 1.27 horizontally and 1.37 vertically.

In addition to the TV monitor the subject pilot could use the radio altimeter, an airspeed indicator, and a rotor RPM indicator. The TV camera was mounted either on the skids or at eye level and could be slewed or rendered immobile. The results for the tested flight phases is as follows.

Take Off: There was no appreciable difference between performance using the TV and performance under VFR. There also was no marked difference due to camera mounting or mobility.

Low Level Cross Country: Three sets of instructions were used. For VFR the pilots were asked to fly as fast and low as possible, for one of the TV flights to hold airspeed at 60 knots and fly as low as possible, for the other TV flight to hold absolute altitude at 300 feet and fly as fast as possible. The performance under the three sets of rules is summarized in Table II.

It should be remembered however that there was always a check pilot aboard who was VFR. The numbers might be slightly different if the situation were operational and the pilot were solely dependent on the displayed information.

TABLE II. MEAN AIRSPEED AND ALTITUDE FOR EACH FLIGHT OF THE CROSS-COUNTRY LOW ALTITUDE MANEUVERS

		VFR	TV Constant Alt. Variable A, S	TV Constant A/S Variable Alt.
Subject 1	Altitude	140	318	232
	Airspeed	64	68	60
Subject 2	Altitude	126	306	216
	Airspeed	72	65	58

Hover: Performance with the various displays when attempting to hover is shown in Table III.

TABLE III. MEAN ABSOLUTE ERRORS FOR THE DIFFERENT MEASUREMENTS OBTAINED FOR HOVERING OPERATIONS

Condition	Fore/aft, Feet	Left/right, Feet	Altitude, Feet	Heading Degree
VFR	2.53	1.60	1.7	1.1
Eye level - mobile	7.12	2.00	1.1	2.0
Eye level - immobile	6.90	2.22	1.9	1.7
Skid level - mobile	7.08	2.15	2.1	2.2
Skid level - immobile	7.98	2.71	1.7	1.0

There were no differences between any of the TV treatments, but there is a marked and significant difference between TV and VFR in fore/aft displacement errors. Otherwise there is little difference between TV and VFR.

Landing: Altitude and airspeed performances comparing TV with VFR are shown in Figures 6 and 7. Using the TV, the pilot has a tendency to "sneak up" on the landing pad and sort of feel his way down. This technique may be simply due to the field of view of the TV which is such that if a large flare is used the ground disappears. The position error at touchdown was also recorded. With TV the mean lateral error was 12.8 feet and the

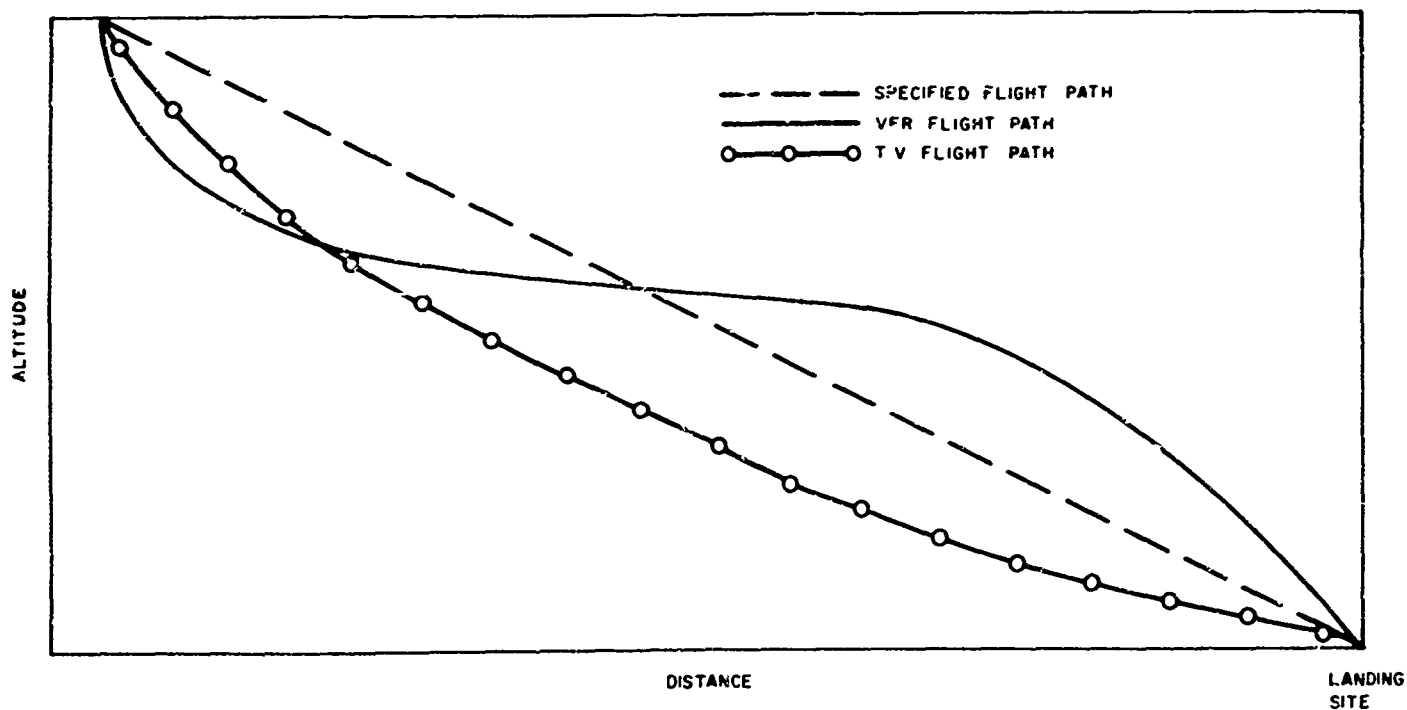


Figure 6. Schematic Representation of Typical Landing Pattern for VFR and TV Viewing Conditions

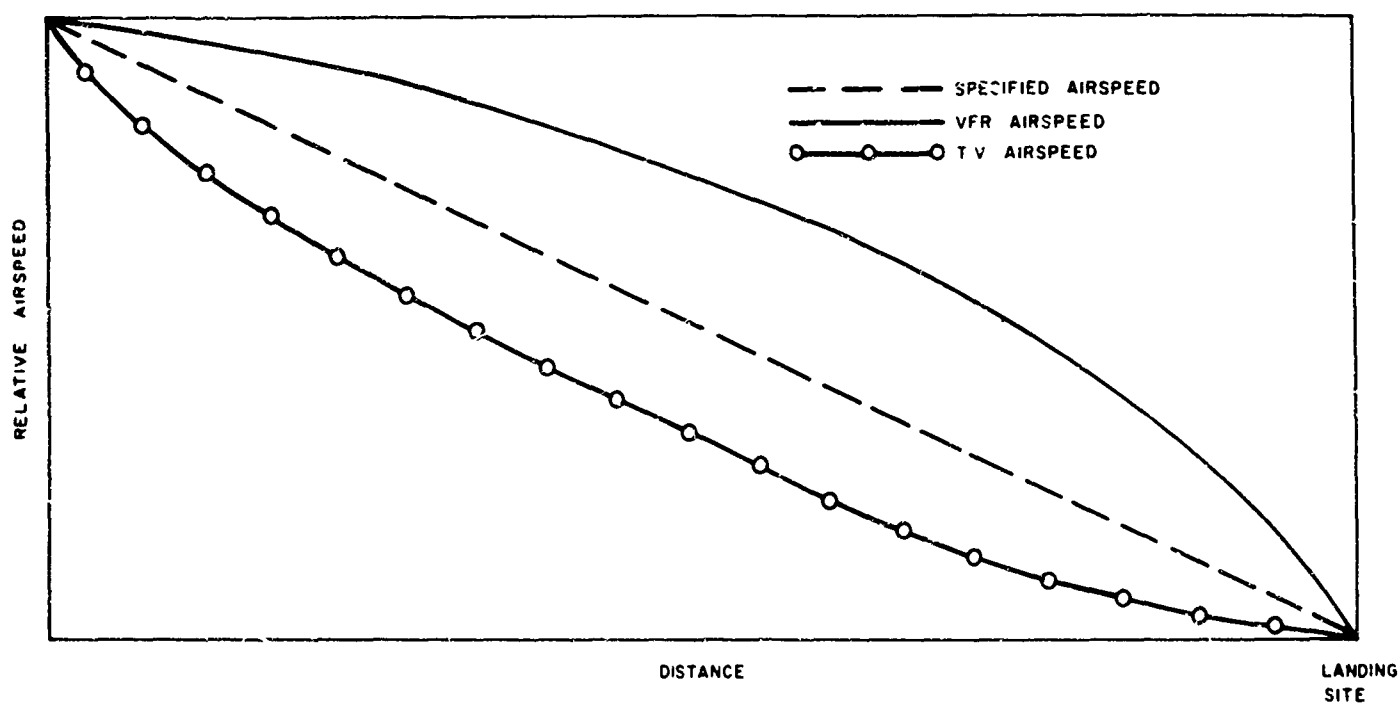


Figure 7. Schematic Representation of Relative Airspeed During Landings for TV and VFR Conditions

mean fore-aft error was 39.4 feet. No measurements were made for the VFR flights but these can be considered as being negligible.

The study showed that the helicopter can be landed in a restricted area using the TV as a primary instrument if conditions are highly favorable. This means little or no crosswind and an approach to the pad that is obstacle free.

The authors of the study interestingly suggest that the contact analog affords better control than TV for landing but, of course, the displayed TV data is highly reliable. They conclude that, "The best answer seems to lie in a synthesis of the two systems. The TV is best for validating and updating the contact analog. The latter display will give the pilot something that is easy to respond to."

ING In a similar study Kibort and Drinkwater (1964) used an R4D (DC3) aircraft fitted with a closed circuit TV to test the effectiveness of the TV display for the final phase of landing. A turreted camera was mounted on the nose of the aircraft and an additional camera just forward of the tail wheel. The output of the tail camera or the nose camera with any of the three lenses could be fed to a 17-inch monitor (14-inch width) that was mounted to subtend about 16 to 17 degrees at the pilot's eye. The fields of view and magnifications corresponding to the tested conditions are shown in Table IV. All flights were scheduled in clear weather when the wind was between 0 to 15 knots. "The safety pilot flew the aircraft until it was aligned with the runway on a 3 degree glide path (using the visual mirror glide path system) 2 to 3 miles from the runway threshold. Control was then given to the subject pilot who continued the landing approach through the touchdown phase and rollout."

ING Results are shown in Table IV. There were no significant differences among conditions with respect to contact g. The standard deviation touchdown error scores for TV were all significantly different from normal flight at the 2 percent confidence level. "Analysis of the mean touchdown error ("T" test) indicated a significant difference between all the TV type landings and the normal visual approach."

TABLE IV: PERFORMANCE WITH TV DURING LANDING

Display	Approximate Field of View, Degree	Magnification Factor	Standard Deviation Touchdown Error, Ft.	Average Touchdown Error, Ft.	Absolute (Mean) Touchdown Error, Ft.	Standard Deviation, Contact g	Mean Contact g	Number of Landings	Aborted Landings
Normal			373	-90	270	0.159	0.339	43	0
4 inch Aperture	18 - 35		426	-132	284	0.141	0.341	42	0
Nose TV 12 mm	48	0.34	479	159	395	0.175	0.378	43	2
Nose TV 25 mm	23	0.73	652	59	518	0.205	0.396	41	4
Nose TV 50 mm	11	1.55	726	-126	542	0.130	0.326	37	0
Tail TV 12 mm	48	0.34	764	270	607	0.159	0.321	38	3

In the approach phase the authors state that the pilot needs airspeed information when flying normal contact, airspeed and rate of climb with the 4-inch aperture, and airspeed, rate of climb, and altitude with the TV displays. They also conclude that magnification is one of the most important variables and that high magnification is desirable because it results in increased display gain. This view should however be tempered with judgment for during flare and touchdown using the telephoto lens the field of view was so narrow that at times the runway was lost due to cross winds.

The authors implication is that TV displays may prove highly useful for landing provided the system is carefully designed, provided height and height rate information is added, and provided the pilot is afforded sufficient practice with such novelties. The authors suggest that a possible idealized display would have an acceptance angle of at least 45 degrees with height, height rate, and displacement information superimposed along with a gain similar to that obtained with the telephoto lens (1.55 magnification ratio). Unfortunately these idealized requirements yield a display that, if viewed from 18 inches, would be about 30 inches across.

In all of these studies the issue of magnification is paramount. Apropos of the general problem of magnification one might consider what is predicted from perceptual theory. For purposes of this discussion let

"optical slant" define the angle between the line of regard and an observed surface, say the surface of the earth. Consider the simple case illustrated in Figure 8. (Adapted from Carel, 1961)

Let the picture be conceived as the result of the projection to the station point, but let the eye be somewhere on a line between the station point and the center of the picture as shown in Figure 8. If the eye is between the station point and the picture, call its magnification greater than 1.0, and if beyond the station point, magnification less than 1.0.

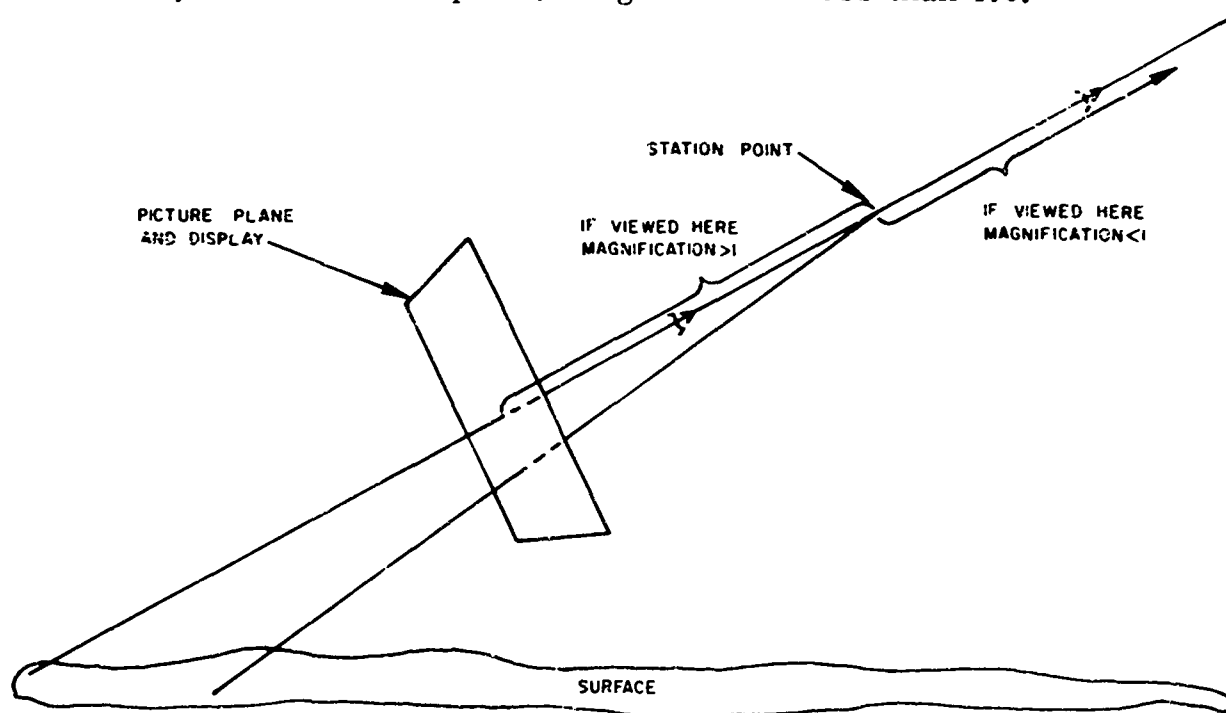


Figure 8. Diagram Illustrating Magnification

From a theoretical point of view, the perceptual consequences of magnification can be predicted. It follows from the texture perspective hypothesis that magnification greater than 1.0 will yield optical slant estimates steeper than normal as shown in Figure 9. Conversely, magnification less than 1.0 will yield optical slants shallower than normal, as shown in the same figure. In fact, when predicting from the texture perspective hypothesis, no reference need be made to "normality" for the hypothesis states a relationship between the property of an optical image and resulting perception. For convenience, "normal" is defined as estimates which would be obtained with a magnification of 1.0. The reader may examine at first

hand some of the effects of magnification by looking through the right and wrong ends of binoculars.

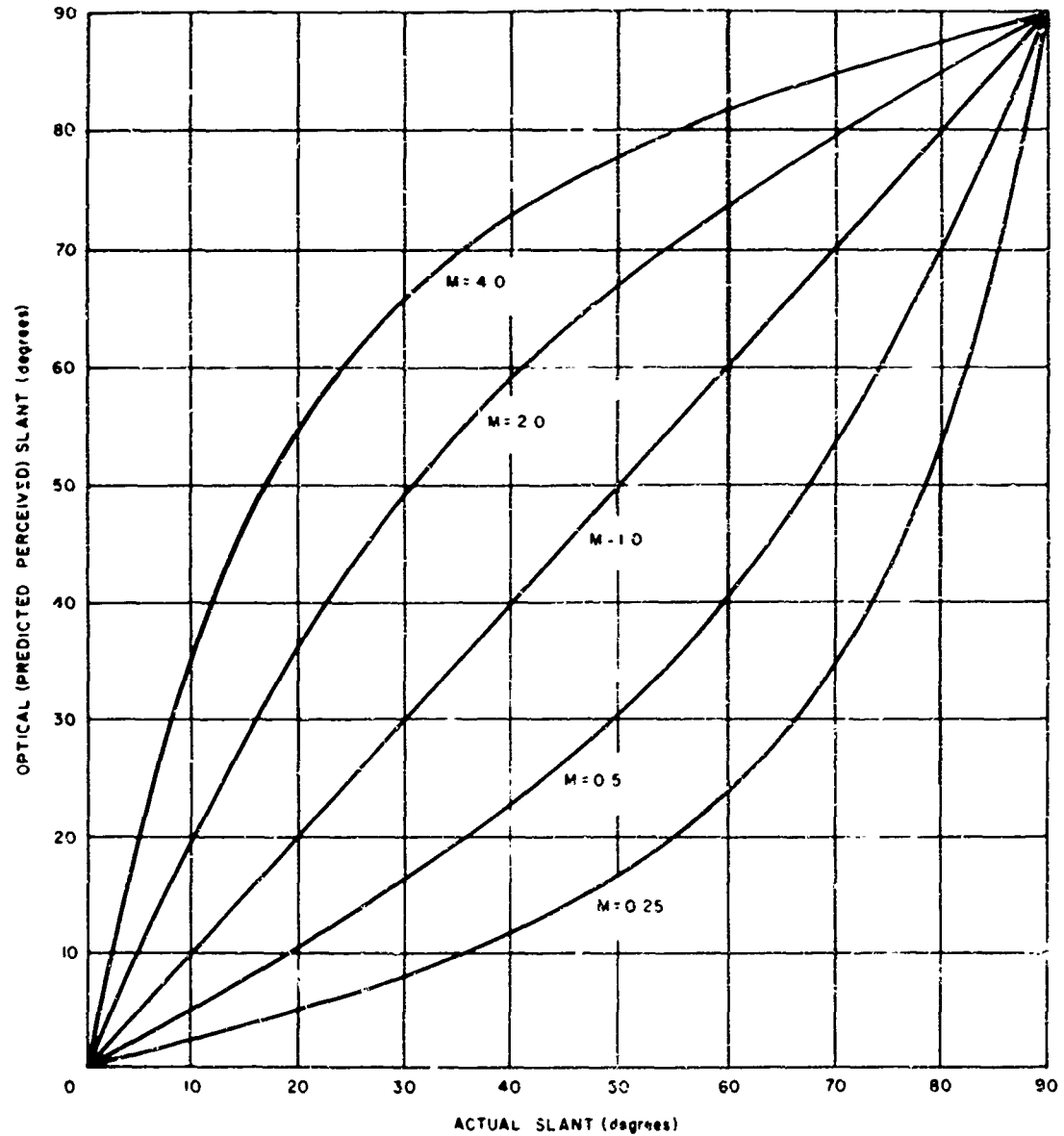
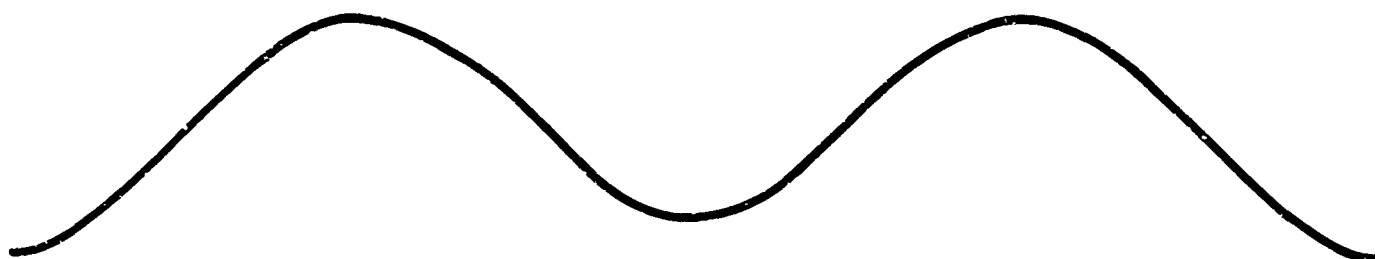


Figure 9. Relation between Physical and Predicted Perceptual Slant with Magnification as a Parameter (Individual Subject's Constant Error Must be Added)

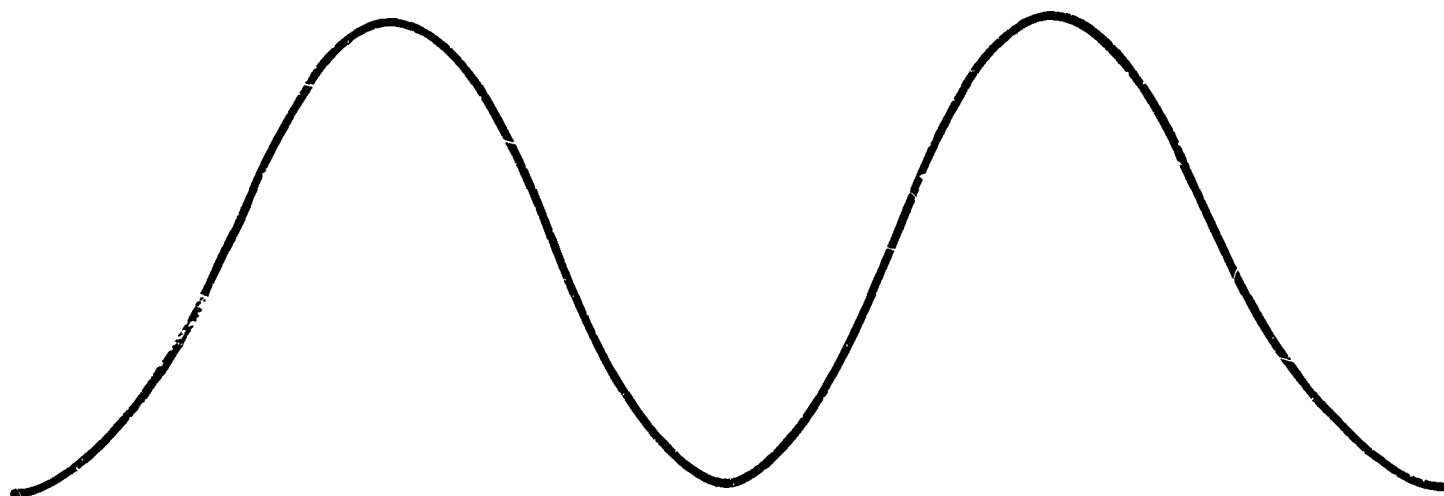
Magnification also has some qualitative effects on the impression of the ride of the vehicle. With compression (magnification less than 1.0) the ride appears very silky and smooth. If a 3.1 compression, i.e., magnification 0.33, is represented as



then unit magnification, 1.0, might be represented as



and magnification of 3.0 as



Therefore a discrepancy may arise between the "g" profile and the "visual" profile. For other than unit magnification this could make the pilot somewhat uncomfortable. There is some evidence that a conflict of information from the visual and postural senses makes people sick.

The entire theoretical argument is based on the supposition that the display medium itself is unobtrusive. The attempt to make the display screen itself "invisible" is much sought after in the movie industry where the intent is to have the observer pay attention to the image on the screen, not the screen itself. Practically, however, it is likely that the eye will be accommodated to the focus of the display medium, for the plane of the display itself may be perfectly visible. The perceptual effects of this fact coupled with the presumed effects of magnification are difficult to predict. The issue has not been settled experimentally and the matter stands unresolved.

Some Requirements for Literal Displays

The conclusions drawn from the above cited empirical studies may be used to aid in establishing the limits of a literal display for landing. From the foregoing studies we know that in a literal display there is increasing hazard in departing from a magnification factor of 1.2. If this value is accepted then the appropriate size of the display may be determined by analysis. In general it is desirable that the pilot see where he is going — not where the aircraft is pointed but where it is going. For fixed wing aircraft the incongruence between the aircraft longitudinal axis and its velocity vector relative to the ground is determined by wind and angle of attack. During landing either drift angle or angle of attack may be larger depending on conditions and type of aircraft. In either case these angles may vary from a few degrees to larger than twelve degrees. For high performance single or dual place aircraft the angle of attack in approach and landing will usually exceed the lateral drift angle. This flight characteristic then should be used as the basis for establishing minimum display size for this type aircraft. In the elevation dimension the general rule for the size of the literal display may be calculated from the relation:

$$S = d \tan (a_L + 3^\circ)$$

where

$$S = 1/2 \text{ display height}$$

- d = viewing distance
- a_L = maximum angle of attack during landing
- 3° = constant to assure visibility of this amount around the velocity vector.

The assumptions buried in this simple calculation are that the horizon null is at display center when aircraft pitch equals 0 degrees and that unit magnification is used. One must multiply by whatever magnification factor is desired. For example, with a display viewing distance of 24 inches in an aircraft whose maximum angle of attack during landing is 7 degrees, the appropriate vertical display dimension is: $24 \text{ by } .176 \text{ by } 2 = 8.4 \text{ inches}$. In a raster display with a normal 4:3 format and the major dimension horizontal, the display size is 11.2 by 8.4 inches. This is a simple way of calculating the minimum size for a literal display under the assumptions noted. The display size could be reduced somewhat by letting the horizon null position be above display center at zero pitch. This would be feasible if the display were used as a flight display only during landing when the aircraft is predominantly nose-high. However the display will be used for flight control in other modes of flight — for example, terrain following — where it is not advantageous to have the horizon offset. It is not desirable to have the horizon offset in one mode and centered in another as the pilot would be required to change "set" from mode to mode. This would undoubtedly lead to error so the gambit of using the offset horizon to reduce display size should not be employed without empirical test. The physical display size could also be markedly reduced by placing the display very close to the eye — as in the helmet mounted CRU. The important thing is the angle subtended by the display and in the helmet mounted display the angular size can probably be made sufficiently large.

In the previous paragraphs the problems of longitudinal control and display coverage were emphasized. In considering the problem of lateral control during landing, the importance of azimuth coverage in a literal display is even more evident. In contact landings the incidence of accidents,

go-arounds, or hard landings due to mis-alignment with the runway are few compared with incidents caused by under or over shooting. When seen, the runway and its surroundings provide excellent lateral but mediocre longitudinal guidance. This guidance depends, of course, on the runway being visible and in a literal display if the landing spot, whether strip or carrier, is not visible then many of the advantages of the literal pictorial display will have been lost. The consideration for lateral coverage is the maximum cross track heading likely to occur during the approach phase when the runway is being used for guidance. A reasonable value to start with is ± 15 degrees. The size and magnification factor of a literal display determine only whether or not the runway will be shown continuously in the space represented on the display during approach and landing. Whether it will be seen or not depends on runway size and contrast as well as system resolution. Runway size as it appears on the display may be easily calculated. Figure 10 shows the literal size of a 200 by 1000 foot patch* with unit magnification on a display viewed at 18 inches. The same information is presented numerically in Table V. At a 2-degree depression angle which would correspond to a constant flight path angle of 2-degrees, the "carrier", subtends only .025-inch in elevation at a range of 4 miles (the acquisition range of SPN-10 ACL mode). On a 500-line 8-inch display this is only two raster lines at most and in the conditions of flight it is difficult to predict whether or not it would be visible. With adequate contrast it could certainly be seen at one mile.

From the evidence gathered to date, the use of an unaided literal vertical raster scan display as the primary instrument for landing either a fixed or rotary wing aircraft appears risky in spite of the promising results obtained in the periscope and television studies. The major difference between the periscope display used by Roscoe and practical raster scan displays are size and resolution. Roscoe used an 8 by 8 inch display -- a large piece of cockpit real estate -- and a system whose resolution approached that of the eye.

*The length of the Enterprise is 1040 feet and the widest part of the deck is 252 feet.

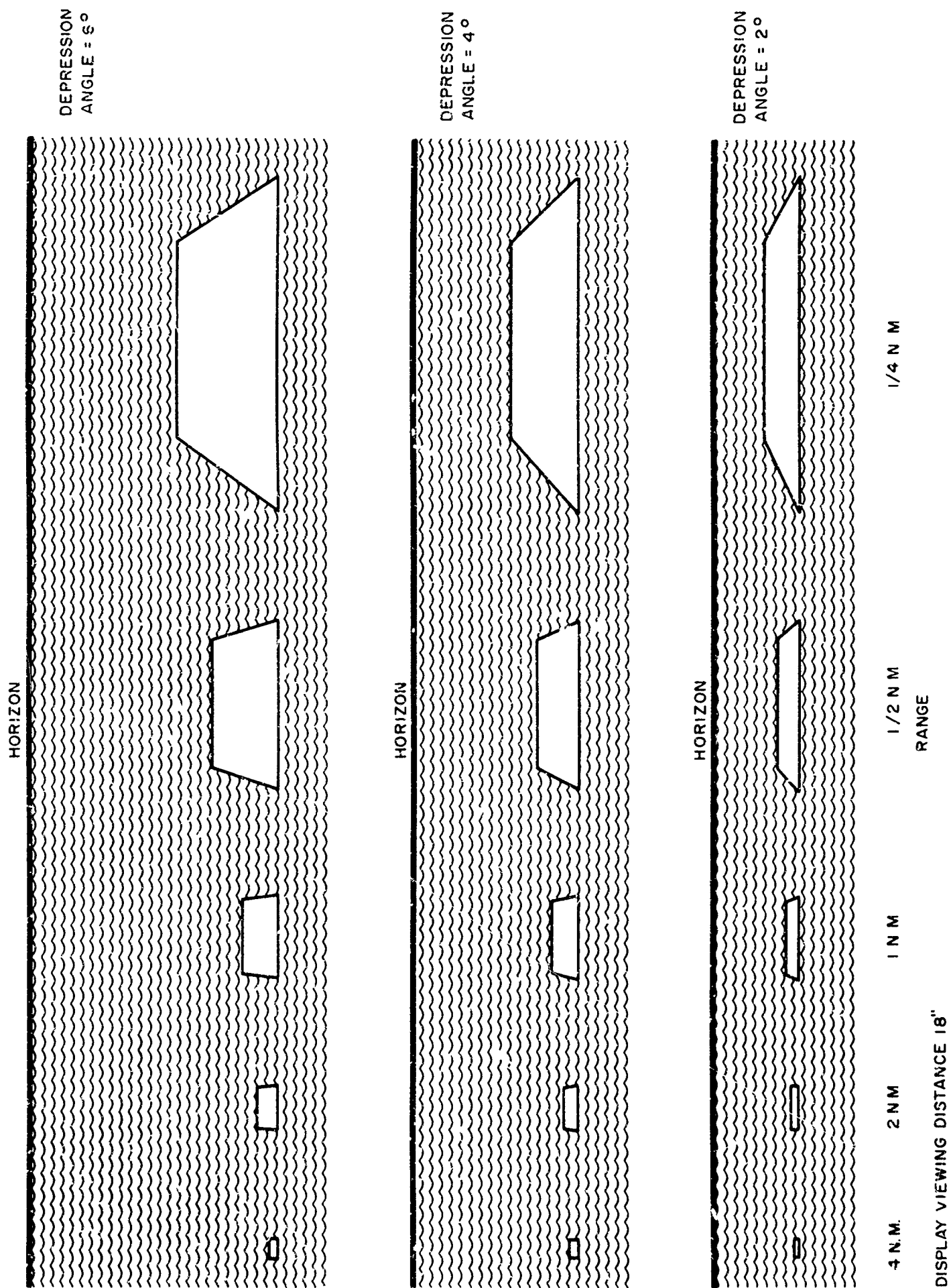


Figure 10. "Runway" Appearance

TABLE V. DIMENSIONS OF RUNWAY ON DISPLAY, INCHES

	Depression Angle, degrees	Range to Runway				
		24000	12000	6000	3000	1500
Distance below horizon	2	0.69	0.69	0.69	0.69	0.69
	4	1.26	1.26	1.26	1.26	1.26
	6	1.89	1.89	1.89	1.89	1.89
Width far end	2	0.14	0.28	0.51	0.90	1.44
	4	0.14	0.28	0.51	0.90	1.44
	6	0.14	0.28	0.51	0.90	1.44
Width near end	2	0.15	0.30	0.60	1.20	2.40
	4	0.15	0.30	0.60	1.20	2.40
	6	0.15	0.30	0.60	1.20	2.40
Height, near to far end	2	0.025	0.048	0.090	0.157	0.251
	4	0.050	0.097	0.180	0.315	0.504
	6	0.076	0.145	0.270	0.472	0.756

Unless the CRT could approach this size and have at least a 1000-line raster scan without sacrifice of frame rate, an unaided literal raster vertical display as the primary instrument for landing does not appear promising. If the literal display is mixed with additional guidance information then the display has considerable merit for there are some intrinsic advantages to the literal display for landing. The information the display shows is undoubtedly reliable, landmarks can be used for navigation checks, and because of the great amount of potential information in the display, the pilot may choose an alternative course of action should things go awry. The literal display also takes advantage of the ingrained perceptual habits that pilots have spent years acquiring. These advantages can only be obtained if the system satisfies the requirements of high resolution, near unit magnification, and large coverage,

THE ANALOG VERTICAL SITUATION DISPLAY

Display Characteristics

The contact analog display is the point perspective projection of a three-dimensional model to a picture plane. The model contains reference objects significant for flight performance such as a surface representing the local horizontal, usually called the ground plane, a surface representing the command path for the pilot to follow, usually called the flight path, and other surfaces or objects useful during different phases of the mission. An illustration showing the relation between the environment, the model, and the display is shown in Figure 11. The computer that paints the display may also paint conventional non-perspective symbols in the plane of the display; circles, crosses, and the like. The hallmark of a contact analog is the display of surfaces whose kinematics are similar to those of real surfaces in the natural visual environment. In the microcosm of the panel mounted display where magnification may be other than unity, the displayed surfaces will still follow the laws of motion perspective and thus provide information coded in a fashion analogous to the coding provided in visual contact flight.

The major elements in the contact analog display are the ground plane and the command flight path — the "highway in the sky." The use of the ground plane is fairly well understood, although it must be said in passing that it does not necessarily represent the ground but, for aircraft application, simply a horizontal reference surface that, on the display, moves precisely in the same way as does the real ground in response to aircraft maneuvers. The intended application of the command flight path, however, is not so well understood for in some versions of a so-called contact analog the flight path has been used as a compensatory tracking display to provide heading and elevation steering errors, a singularly inappropriate use of this display concept. As the distinction between the use of the flight path to provide steering error information and the use of it to provide a command path in space bears emphasis, we shall clarify the issue by reproducing here an excerpt from an earlier discussion by Carel (1960).

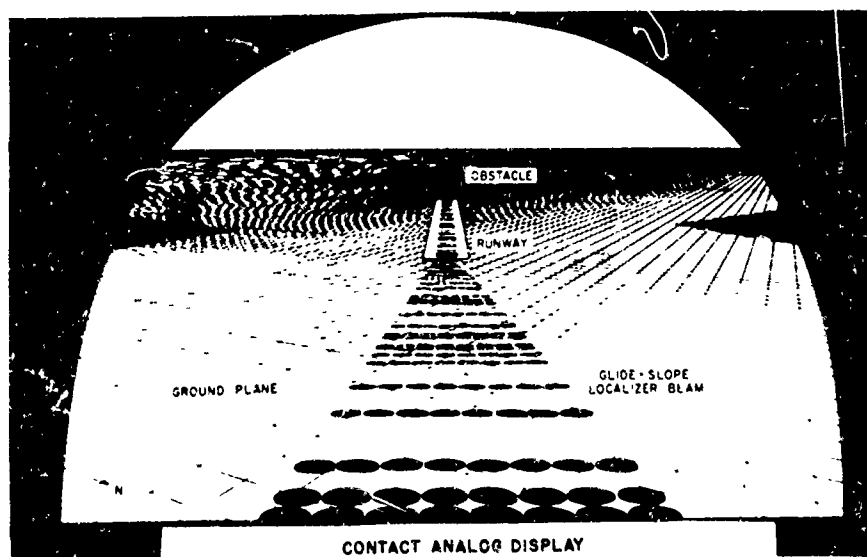
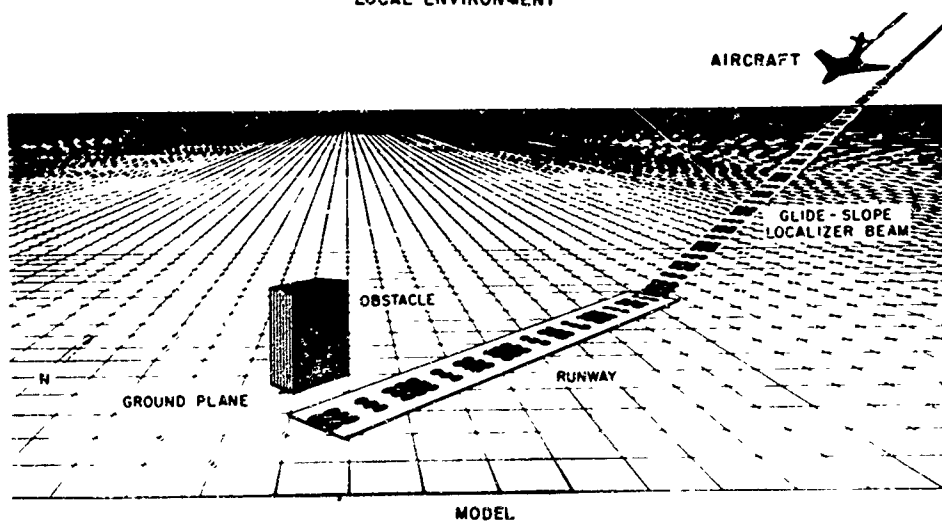
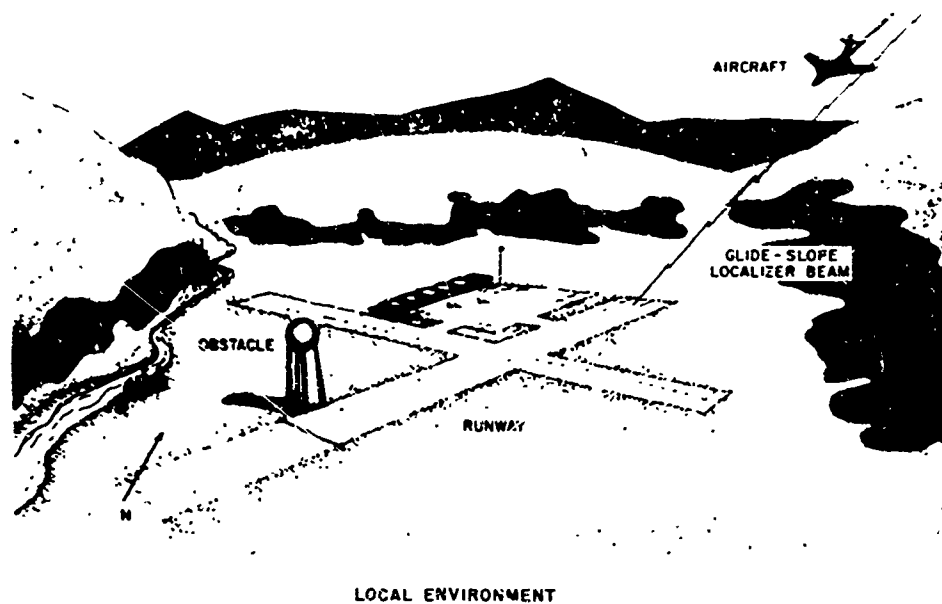


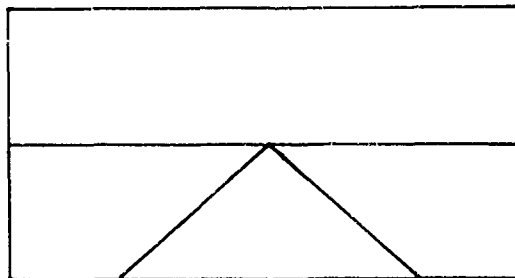
Figure 11. Relationships between the Local Environment, the Model, and the "Contact Analog" Display

"Normally the pathway represents a fixed path in space along which the pilot flies much like driving a car down the road. Presumably the trajectory of this pathway is generated to realize the optimum safe performance potential of the aircraft. It represents, in short, the best path to the end goal. To date it has been taken as axiomatic that this pathway is literally fixed in space. This has been done because in display, it is desirable that any motion of the ribbon or path be attributable only to rotation or displacement of the aircraft. The whole intent of this display is to induce in the pilot a sense of motion so that he is always under the impression that he, rather than the represented surface, is rotating or translating. How to induce this perception in the pilot is not completely understood. However, the writer believes that this perception would be seriously compromised if, at times, the path on the display moved because the aircraft moved and at times it moved because the path was recomputed without the knowledge of the pilot. To be believable as a real world substitute this display must reflect the expectancies of the pilot.

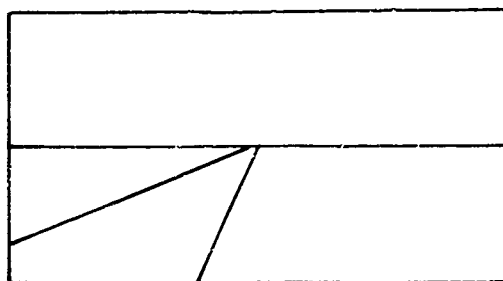
An additional argument in favor of keeping the pathway fixed is related to one of the reasons why a pursuit tracking task is easier than a compensatory tracking task. In pursuit tracking the tracker has knowledge of both target changes and his error. In compensatory tracking he has knowledge of only the total error. In the pursuit case the tracker can separate out his error and target perturbations. Pursuit tracking is similar to flying the stable path and compensatory tracking to flying a continually recomputed unstable path.

As a simple instance of the ambiguity inherent in using an unstable ribbon for path director, consider the following:

- 1) Let the pilot be flying straight and level, dead center on a flight ribbon. The picture might look like this:



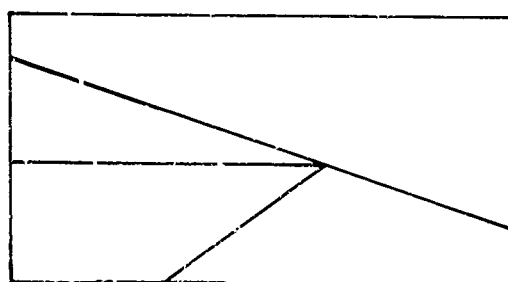
- 2) Let him fly the same heading, twenty seconds later the picture looks like this:



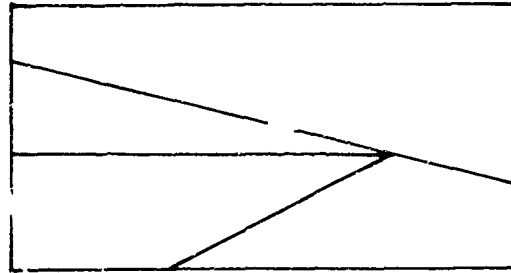
If it is assumed that the path took its new position gradually (smoothed computation) the pilot may interpret this in one of three ways:

- 1) He has drifted off track.
- 2) A new track is being computed.
- 3) A portion of the computer or generator has failed.

It may be argued that the distinction between 1) and 2) makes no difference since in both instances he should turn left. Let us see what happens if he turns left. If he turns left and gets back on the track either hypothesis 1) or 2) may have been correct. Let us suppose, however, that he rolls left.



However, the path stays out in front of him because it is still being recomputed.



He may then conclude that:

- 1) The path is being recomputed
- 2) A portion of the computer or generator has failed.

It is obvious that the display is still ambiguous.

Such examples of ribbon configurations could be multiplied ad infinitum and it seems, at times, that well wishers have indeed made an infinite number of such suggestions. However, most of them violate the basic hypothesis directing the efforts: the surfaces represented in the display encode information in a fashion similar to the way it is encoded in natural visual world. One of the most important display characteristics that must be met to achieve this perceptual similarity is display dynamics. The displayed surfaces must behave like natural surfaces. They may be placed at 50,000 feet; they may be curved, banked, or vertical, but they must respond exactly as if they were rigid fixed surfaces in the real world. If they do not respond correctly what the pilot expects to see is contradicted, representing a possible source of error and confusion. The concept of "expectancy" as it applies to the dynamics or motion of this type of display cannot be too strongly emphasized. Through experience the pilot has built up a knowledge and library of expectancies of how the visual world responds to various aircraft maneuvers. A display system that is intended to be a compelling substitute for this visual world must have the same kind of response characteristics.

A still different way of using the flight path is to use it as a predictor instrument. Essentially this instrument predicts the future of the variable the operator is controlling. In the case of the aircraft this could be the flight path of the aircraft (the pathway in the contact analog display could be used for just such a purpose). For example, it could show the path the aircraft will take as a consequence of holding the control stick constant. This, of course is a completely different use of the ribbon. The merit of using the ribbon to indicate predicted flight path rather than command flight path is open to considerable question. If the end target were shown in the display the pilot's job when using the pathway as part of a predictor instrument would be simply to move the controls until the path intercepts the target. This use of the path in the vertical display is very similar to the use of the range ring in the horizontal display where the range ring predicts available range as a function of present performance. "

The value of the flight path as a stable command remains unevaluated except in the few instances that will be discussed in the following paragraphs. To use the path image to provide steering information, however, seems without advantage for the same information can be displayed more cheaply and with less probability of misinterpretation by employing a simple steering dot or circle.

As far as the writer knows there are two designs for contact analog displays that meet the criteria suggested above: the one by Norden and the one by General Electric. Because I am most familiar with the General Electric development, the features of that particular design as well as the G. E. nomenclature will be used to illustrate the contact analog. This is without prejudice to Norden and implies no evaluation; it is only done for the sake of convenience.

We must assume for this report that the display is familiar to most of our readers, and we shall not burden these pages with a further description of its characteristics. A detailed discussion of the human factors requirements for such a display may be found in Carel (1961).

Figure 12 is a pilot's eye view of a portion of the display in one mode of operation. This sequence illustrates a change in heading and altitude with

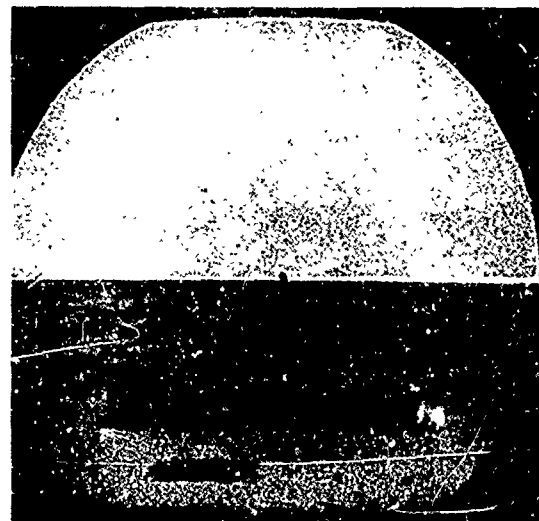
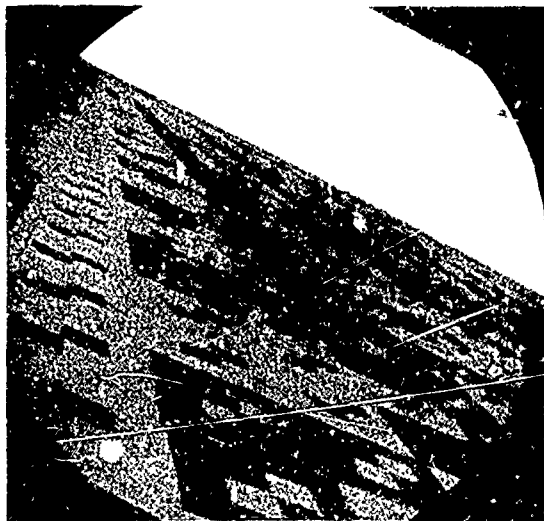
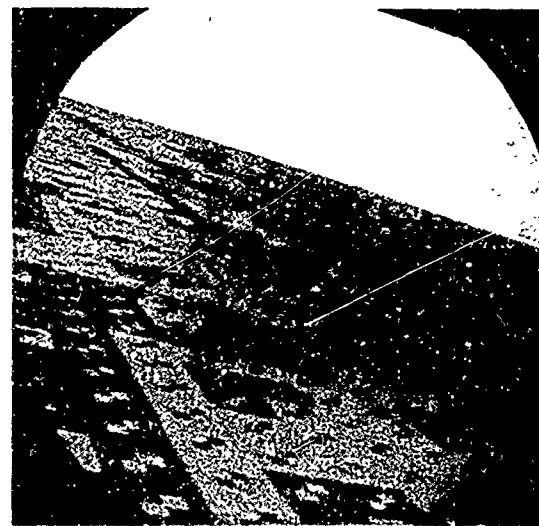
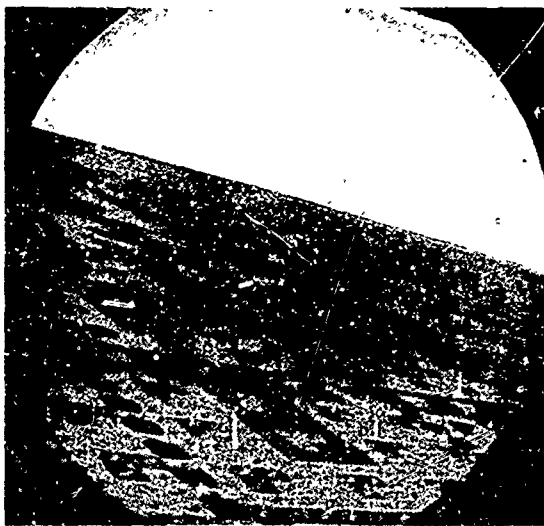
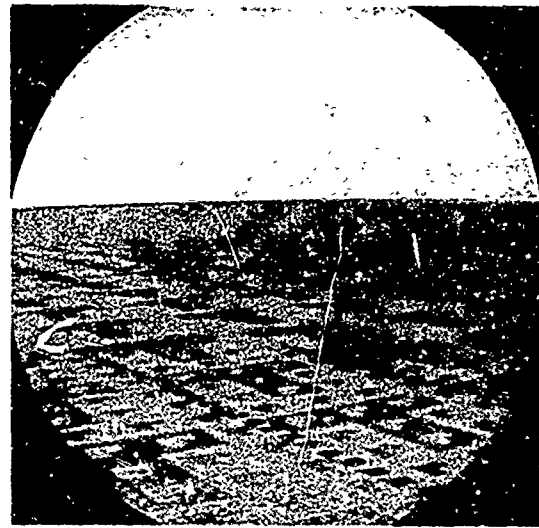
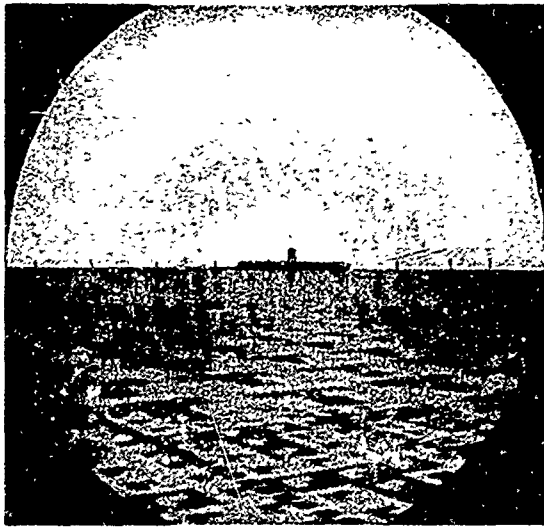


Figure 12. Partial Contact Analog Display

reference to the ground plane. The complete display has the following elements (only the ground plane is shown in the illustration).

- 1) A ground plane (six degrees of freedom).
- 2) A sky plane (three degrees of freedom — rotation only).
- 3) A flight path (six degrees of freedom).
- 4) A few three dimensional objects — obstacles or similar objects (six degrees of freedom).
- 5) A ground patch — runway, checkpoint, I. P., or target (six degrees of freedom).
- 6) Numerous symbols in the display plane.

A sketch of the display elements in the landing mode is shown in Figure 13.

Experimental Evaluation

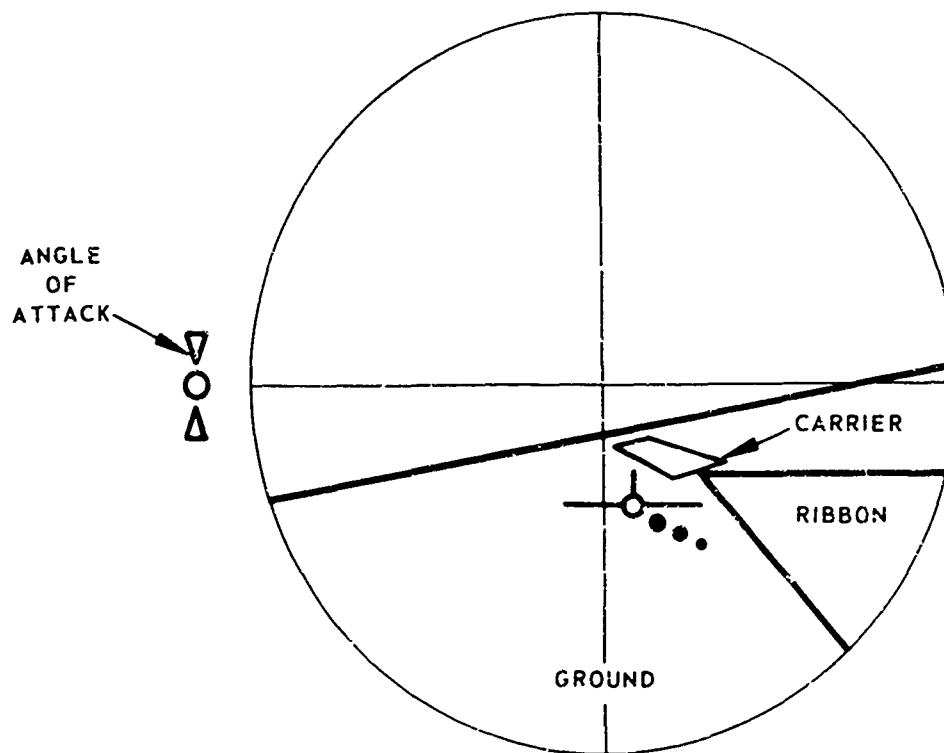
As far as the writer knows, neither the Norden nor General Electric contact analog display has been flight tested in fixed wing aircraft. However, considerable simulator and flight test work has been carried out by Bell Helicopter using the Norden display for rotary wing application.

Bell conducted a systematic and long series of studies using both a dynamic simulator and a test helicopter to determine the utility of the contact analog as a flight instrument. A long series has to do with the evaluation of various features important for the design of the display. Representative of such studies is the experiment (Emery, et al, 1964) in which pilot subjects performed various maneuvers in the Bell dynamic simulator. The display content was varied and the four conditions tested were 1) ground plane alone, 2) ground plane with landing pad, 3) ground plane with pathway border, and 4) ground plane with pathway border and "tarstrips" (black strips perpendicular to pathway edges).

The result of this particular study was that performance improved as command guidance information was added so that pilots did better with the flight path than without.

CONTACT ANALOG

APPROACH AND LANDING (CARRIER)



VIEW DISTANCE = 28 in.
 SIZE = 8 in.
 COVERAGE = $\pm 15^\circ$ AZ-EL
 MAGNIFIC = ≈ 0.5
 FIELD RATE = 60 cps

MANUAL INPUTS
 FIELD ALTITUDE
 APPROACH HEADING
 PITCH TRIM
 RIBBON OFFSET (H_f)

PARAMETERS DISPLAYED					
GROUND	SKY	RIBBON	OTHER	CARRIER	
PITCH ROLL HEADING N VEL E VEL MANUALS	OPTIONAL	SAME AS CLIMB OUT	VELOCITY VECTOR ANGLE OF ATTACK PITCH RATE TURN RATE	INITIAL N INITIAL E N VEL E VEL HDG LENGTH WIDTH	<ul style="list-style-type: none"> • DRIVE CARRIER WITH GROUND OR SEPARATELY? • CHANGE REAL SIZE OF CARRIER AS FUNCTION OF RANGE

Figure 13. Contact Analog Display for Fixed Wing Aircraft

The consensus of these studies as a whole is that the contact analog, if designed correctly, provides the helicopter pilot with one of the few techniques that allows instrument approach and hover. In the most recent study published by Bell (Dougherty, 1964) a comparison was made between performance using the contact analog and performance using standard instrumentation. Two groups were trained to criterion and performance equivalence using either of the two display systems. The Bell simulation facility was used. Subjects were required to hold command altitude, heading, course, and air-speed. A digit reading side task was then introduced in which the required reading rate was varied. The argument is that the display system that is easier to use will allow more time for the side task before suffering a performance decrement.

The results indicate that there was little difference in performance using either display system when the pilot was not stressed. When the task load due to the side task increased, performance with the contact analog remained relatively stable whereas performance with the standard instruments deteriorated with increasing load.

A figure summarizing the performance data is reproduced in Figure 14. The clear result is that information can be assimilated more rapidly with the contact analog pictorial display with the happy consequence that the pilot has time available for the side task. The authors suggest that the superiority of the pictorial display may be attributed to three factors.

- 1) The pilot may more quickly assimilate qualitative information from the pictorial display.
- 2) Using conventional information the pilot samples one parameter of information per glance. With the pictorial display he accumulates information on more than one parameter per glance.
- 3) Because of its size, the pictorial display permits use of peripheral vision.

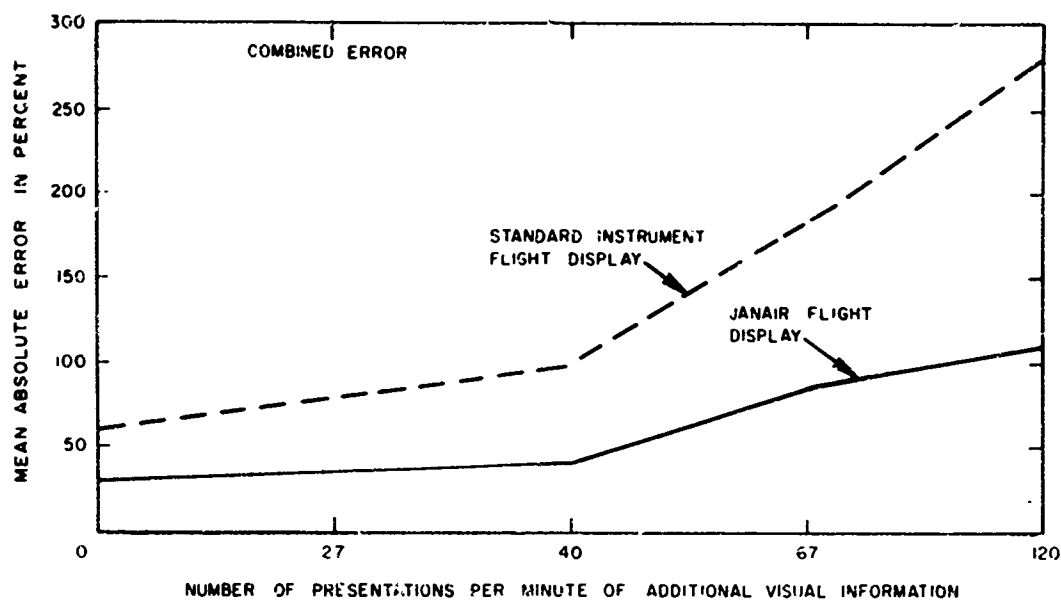


Figure 14. Performance Using a Contact Analog Display and a Standard Instrument Panel Under Different Amounts of External Load

An additional possibility not considered by the authors, is that because of the scale and resultant sensitivity of the display, the contact analog allows error detection sooner and thus permits tighter control. This view would have to be checked by closer analysis but certainly insofar as attitude control is concerned, the sensitivity advantage is all with the contact analog. In a completely unrelated study, Gainer and Obermayer (1964) have shown that in general within the range of values tested between competing multi-dimensional display systems, the display that is most sensitive will yield tightest control of the displayed parameter.

We have placed some emphasis on this particular Bell study because it is one of the few carefully conducted and documented empirical studies that makes a direct comparison between performance using the contact analog and standard instrumentation.

Although the contact analog was originally conceived in the context of fixed wing application, almost all of the simulation and flight test evaluation of the physical embodiment of the concept has been carried out in helicopters. This may simply be historical accident or may be the consequence of relative need — the pressures for adequate helicopter all weather instrumentation are more acute than for fixed wing aircraft. Instrumentation for helicopters was taken over bodily from standard aircraft in spite of the fact that the helicopter is a far different beast — particularly when flying slower than 30 to 40 knots. The helicopter has more degrees of freedom than the conventional aircraft and the distinction between where the aircraft is pointed and where the aircraft is going is much more pronounced. The pilot of the helicopter, therefore, is more interested in the relationship between his attitude, his velocity vector, and critical objects on the ground than is the fixed wing pilot. A display like the contact analog which provides him with this information in a coherent fashion fills a lacuna in the complex of standard instruments. Our opinion, unsupported by evidence, is that the contact analog is much more useful and applicable to the helicopter than to the fixed wing aircraft.

As in the literal display, the selection of appropriate magnification, for the contact analog is important. It will be recalled that suitable magnification for literal displays is on the order of 1.2. There is little or no empirical flight performance data on how magnification in the contact analog affects performance as, to date, this has not been a parameter that could be varied. Analytically, one might suppose that the most pronounced effect of display magnification is on display sensitivity with the concomitant change in performance solely due to that. However, it has been shown analytically that in this particular display, magnification will affect the perceived attitude of the aircraft any time the horizon is not on the display. This effect was discussed previously and will not be belabored here. Theoretically, any distortion is undesirable, but in practice considerable distortion is tolerated if the face of the display medium can be seen. What would happen if the tube face per se could be rendered invisible as, for example, in a high quality head-up display where the image is at virtual infinity is unknown. For practical purposes the magnification limits in panel mounted contact analog displays are from 0.33 to 2.0.

There should be no differential magnification of the various surface elements painted in perspective. Elements in the model may change size, e. g., conceivably to gain detection range the runway could change size in the model as a function of range until range is reached where it can easily be seen on the display at its true size and then locked in at its true size. However, magnification as strictly defined, takes place in the perspective transformation to the picture plane, and differential magnification cannot be recommended unless it can be shown to be beneficial by incontrovertible empirical data.

SKELETAL VERTICAL SITUATION DISPLAY

We have drawn up a series of skeletal flight performance displays for landing that embody the principles expounded in the previous discussion. For modes other than landing, the displays are similar but simpler. These displays show the relationships between a set of inherently related variables by use of a pictorial code. In constructing this pictorial code we have paid no particular attention to shape coding of the various symbols used. While it may be admitted that the physiognomic properties of such symbols are of some importance in order to take the "nonsense" out of the usual assemblage of squares, circles, diamonds and the like, we have chosen to slight symbol shape in order to emphasize the notion that in pictorial displays for flight performance, the way the symbol moves and its relationship to other symbols and their movements is more important than what the individual symbols look like statically. In too many cases the static appearance of competing displays are very similar, and it is only when they move that the striking difference between an organized display and a bag of worms becomes evident. Symbol kinematics are just as important as symbol physiognomy.

It is, of course, not possible to illustrate kinematics in this report, but we have done the next best thing and that is to describe the signals that drive each symbol so that the interested reader — and he will indeed have to be interested — may go through the exercise of visualizing what happens in response to control actions or aircraft maneuvers. The landing maneuver has been chosen to illustrate the display action.

Figures 15 and 16 illustrate the nomenclature used to describe the positioning and action of the display symbols. Figure 17 is a sketch of three different landing situations used to demonstrate how the display will appear in different situations, and Table VI presents the numerical values used to draw the displays. Figure 18 is an annotated sketch of a representative pictorial landing display as it would appear in situation I. Figure 19 shows sketches of the display as it would appear in the situations described in Figure 17 and Table VI. To these displays could be added altitude, angle of attack, and stick commands. Illustrations of display appearance in other flight phases is shown in Figures 20 and 21.

These particular displays evidence certain characteristics desirable in pictorial displays. A pictorial topology is maintained between the position of various symbols. If, in the real world, A is to the left of B is to left of C, so it is also on the display.

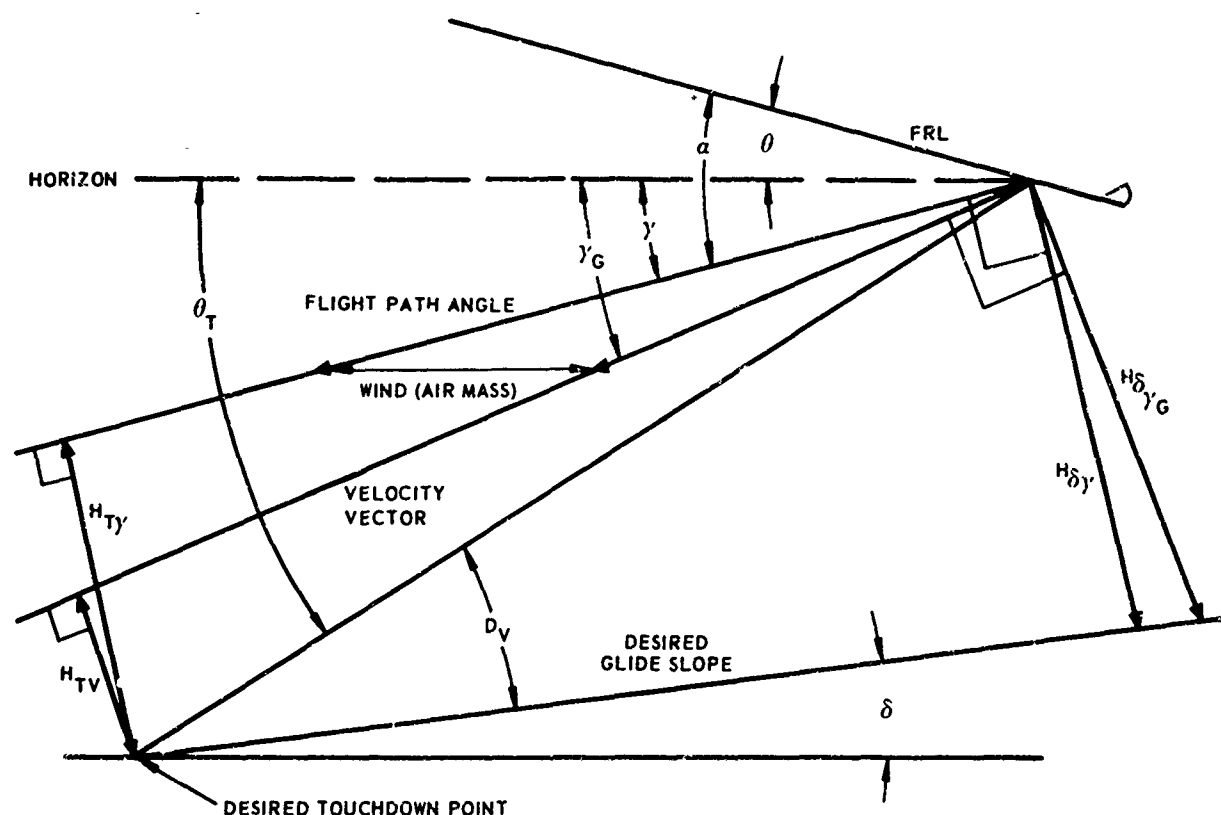
The shape of the symbols themselves would undoubtedly benefit from improvement; for it is a requirement that they be easily discriminable from one another and easily associated with the referent object.

In this particular set of displays the information presented is situational with the errors sorted out so that the pilot is not reduced to tracking a compensatory dot.

Experimental Evaluation

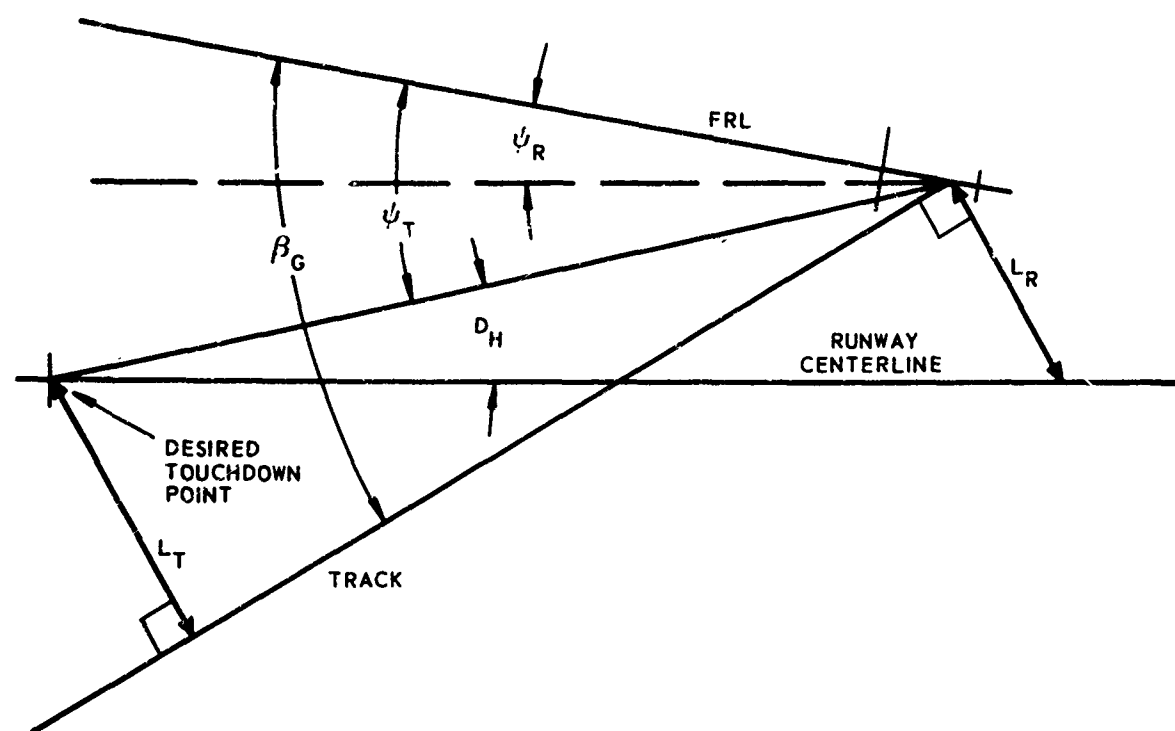
With one exception the merit of the skeletal type of display remains unevaluated by empirical test. The structure of the displays illustrated bears a great deal of similarity to the encoding used on the Sperry HUD, and the Sperry HUD has been tested. A picture of the Sperry HUD display is shown in Figure 22. In a recent article Gold and Workman (1965) evaluated the so-called "windshield display" using a modified B-47 flight simulator.

"Windshield displays with and without flight director have been investigated in a flight simulation program conducted in a modified B-47 flight trainer. Standard panel instruments were also evaluated for comparison. Test subjects included pilots with scheduled air carriers and Federal Aviation Agency (FAA) pilots. Automatic approaches were simulated,



- θ - AIRCRAFT PITCH
- α - ANGLE OF ATTACK
- γ - FLIGHT PATH ANGLE
- γ_G - VELOCITY VECTOR, i.e., FLIGHT PATH ANGLE WITH RESPECT TO GROUND
- θ_T - DEPRESSION ANGLE OF LINE OF SIGHT TO DESIRED TOUCHDOWN POINT
- D_V - ANGULAR DISPLACEMENT OFF DESIRED GLIDE SLOPE (VERTICAL DEVIATION)
- δ - DEPRESSION ANGLE OF DESIRED GLIDE SLOPE
- $H_{\delta\gamma_G}$ - DISTANCE FROM VELOCITY VECTOR TO GLIDE SLOPE - \perp TO V.V. (HEIGHT ABOVE GLIDE SLOPE)
- $H_{\delta\gamma}$ - DISTANCE FROM FLIGHT PATH ANGLE TO GLIDESLOPE - \perp TO γ
- $H_{T\gamma}$ - HEIGHT OF FLIGHT PATH ABOVE TOUCHDOWN POINT
- $H_{T\gamma_G}$ - HEIGHT OF VELOCITY VECTOR ABOVE TOUCHDOWN POINT

Figure 15. Nomenclature, Side Elevation



ψ_R = HEADING WITH RESPECT TO RUNWAY HEADING

ψ_T = BEARING OF TOUCHDOWN POINT

β_G = DRIFT ANGLE

D_H = ANGULAR DISPLACEMENT OFF RUNWAY CENTERLINE
(HORIZONTAL DEVIATION)

L_R = DISTANCE TO RUNWAY CENTERLINE (\perp TO TRACK)

L_T = DISTANCE FROM TRACK TO TOUCHDOWN POINT (\perp TO TRACK)

Figure 16. Nomenclature, Plan View

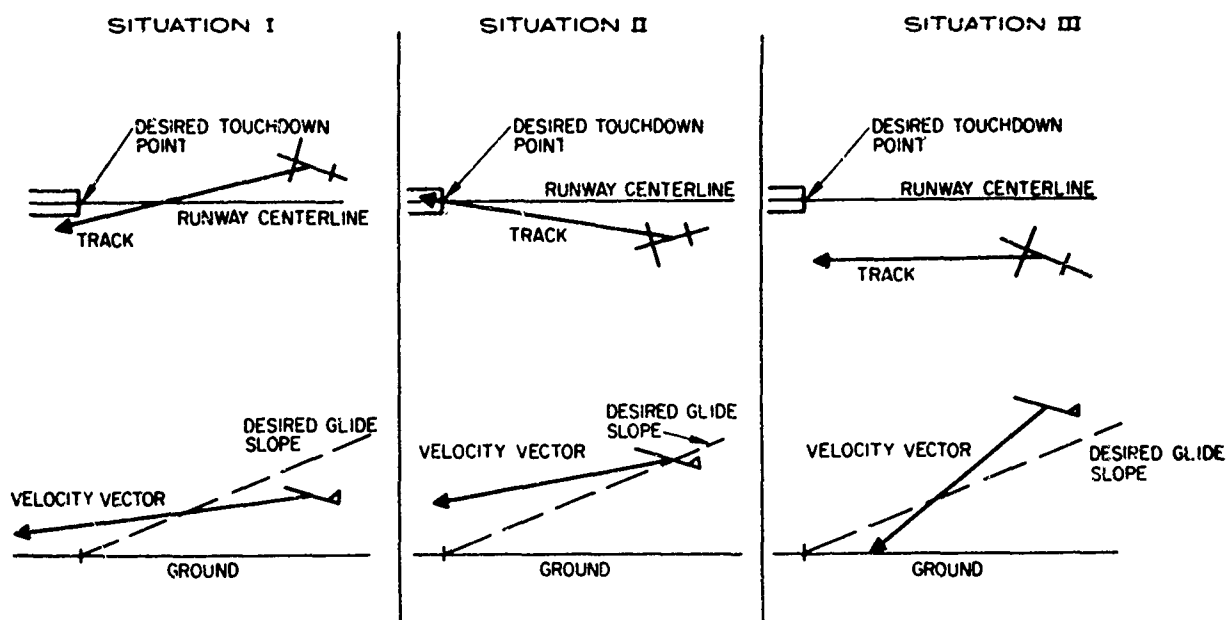


Figure 17. Three Different Situations Illustrated in the Displays
(All Angles Exaggerated; See Table VI for Actual Values.)

TABLE VI. ACTUAL VALUES USED IN SITUATIONS ILLUSTRATED

	SITUATION		
	I	II	III
h , ALTITUDE			
ϕ , ROLL			
θ , PITCH	2°	3°	1°
α , ANGLE OF ATTACK	3°	5°	6°
γ , FLIGHT PATH ANGLE	1°	2°	5°
γ_G , VELOCITY VECTOR	1°	2°	5°
θ_T , DEPRESSION ANGLE OF TOUCHDOWN POINT	2°	3°	4°
D_V , VERTICAL ANGLE OFF GLIDE SLOPE	1°	0	1°
δ , DESIRED GLIDE SLOPE	3°	3°	3°
ψ_R , HEADING WITH RESPECT TO RUNWAY HEADING	3°	2°	5°
ψ_T , BEARING OF TOUCHDOWN POINT	5°	4°	1.5°
β_G , DRIFT ANGLE	7°	4°	5°
D_H , HORIZONTAL ANGLE OFF RUNWAY CENTERLINE	2°	2°	3.5°
L_R , DISTANCE TO RUNWAY CENTERLINE (LATERAL OFFSET)	175'	175'	310'
L_T , DISTANCE FROM EXTRAPOLATED TRACK TO TOUCHDOWN POINT	130'	0	310'
$H_{\delta\gamma_G}$, HEIGHT OF VELOCITY VECTOR ABOVE OR BELOW GLIDE SLOPE	90'	0	90'
$H_{\delta\gamma}$, HEIGHT OF FLIGHT PATH ANGLE ABOVE OR BELOW GLIDE SLOPE			
$H_{T\gamma_G}$, HEIGHT OF VELOCITY VECTOR ABOVE OR BELOW TOUCHDOWN POINT	90'	90'	80'
$H_{T\gamma}$, HEIGHT OF FLIGHT PATH ANGLE ABOVE OR BELOW TOUCHDOWN POINT			
R , RANGE TO TOUCHDOWN POINT		5000'	

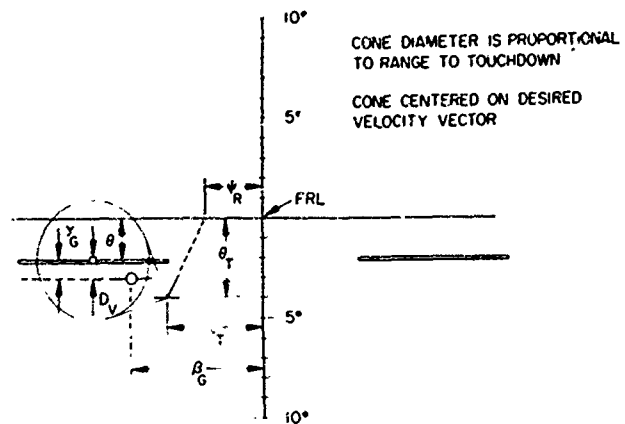


Figure 18. Pictorial Skeletal Landing Display Situation I

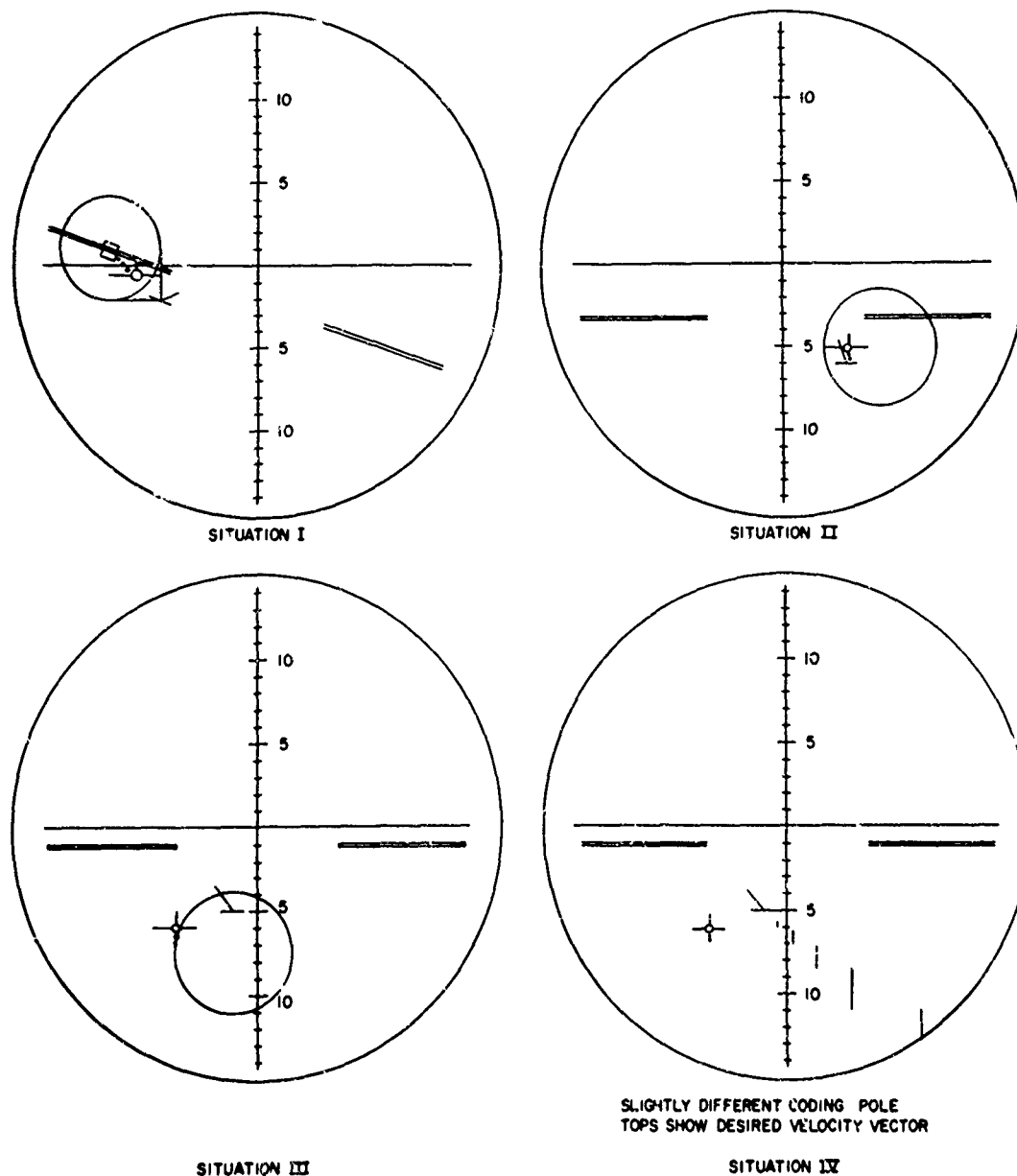
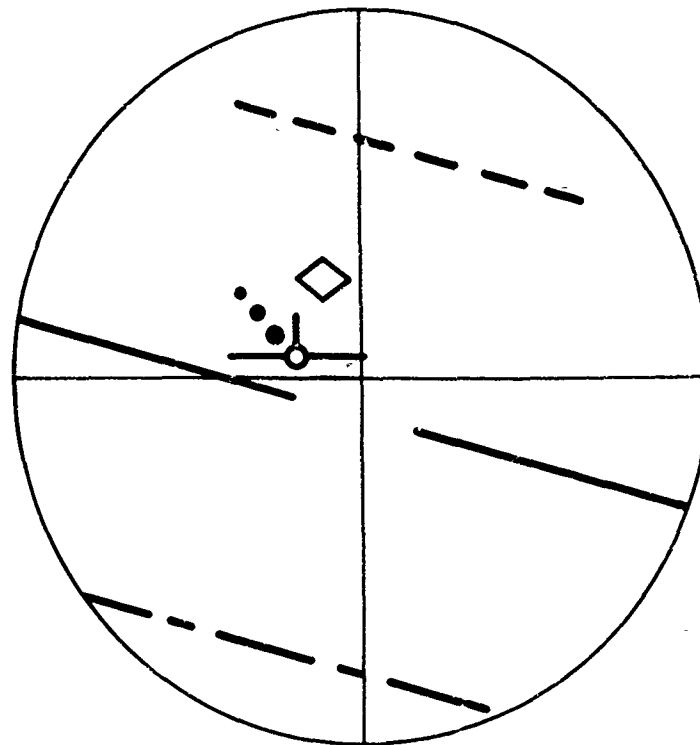


Figure 19. Pictorial Skeletal Landing Display in Various Situations

SKELETAL VSI

TAKE-OFF CLIMB-OUT CRUISE



VIEW DISTANCE = 28 in.
 SIZE = 8 in.
 COVERAGE = $\pm 15^\circ$
 MAGNIFIC = 0.5
 FIELD RATE = 60 cps

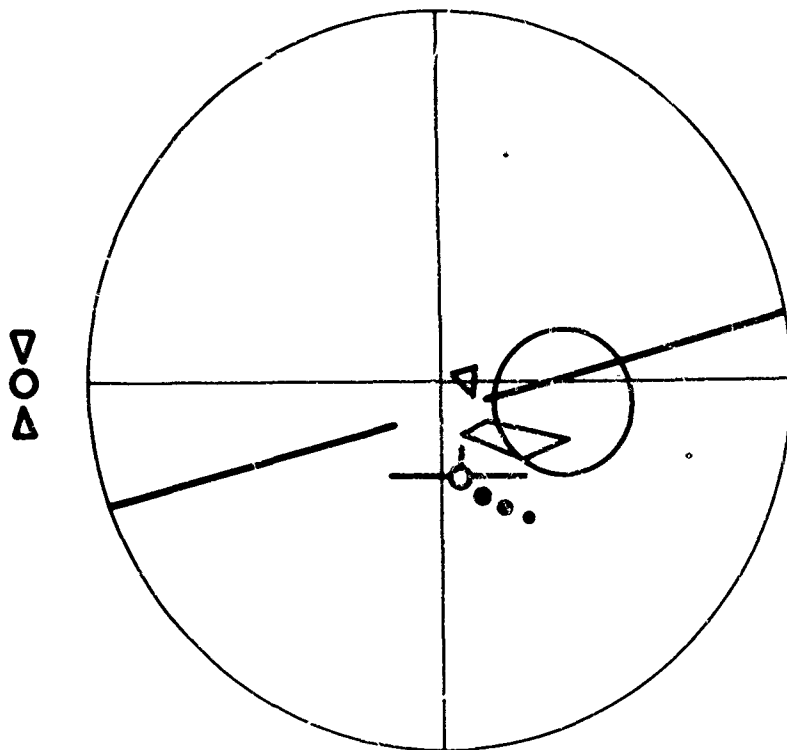
MANUAL
 PITCH TRIM

PARAMETERS DISPLAYED	
PITCH ROLL VELOCITY VECTOR COMMAND VELOCITY VECTOR PITCH RATE TURN RATE	<ul style="list-style-type: none"> • HEADING NUMBERS ALONG HORIZON (OPTIONAL) • PITCH NUMBERS? • ALTITUDE ERROR AIRSPEED ERROR MACH ERROR <div> FOR CLIMB OUT AND CRUISE ON AUXILIARY INDICATORS </div>

Figure 20. Flight Control Display for Fixed Wing Aircraft

PANEL MOUNTED

SKELETAL VSI APPROACH AND LANDING



VIEW DISTANCE 28 in.
 SIZE - 8 in.
 COVERAGE : 15°
 MAGNIFIC : 0.5
 FIELD RATE 60 cps

MANUAL
 PITCH TRIM
 HEADING DESIRED

PARAMETERS DISPLAYED
PITCH
ROLL
HEADING ERROR
BEARING TOUCHDOWN POINT
ELEVATION TOUCHDOWN POINT
VELOCITY VECTOR
VERTICAL ANGLE OFF GLIDE SLOPE
HORIZONTAL ANGLE OFF CENTERLINE
RANGE TO TOUCHDOWN
ANGLE OF ATTACK (AUXILIARY)
PITCH RATE
TURN RATE

Figure 21. Flight Control Display for Fixed Wing Aircraft

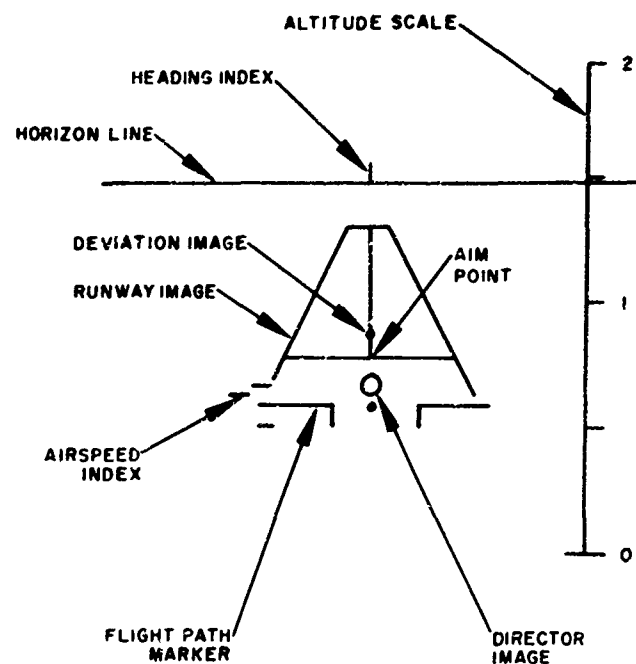


Figure 22. Windshield Display Configuration for Final Approach

and these had several types of flight control malfunctions introduced at different stages during the approach. Performance criteria were selected specifically to measure the pilot's assessment and backup manual control capability in critical all-weather landing situations. The results indicate that pilots exhibit superior performance in both assessment and control tasks when using the windshield display as compared with panel instruments. They can descend to significantly lower altitudes with steady localizer and glide-slope standoffs and recover safely from these conditions. Significantly fewer go-arounds are initiated with the windshield display subsequent to abrupt autopilot malfunctions at low altitudes than with panel instruments."

Whether the superiority of this display is because it is windshield mounted or because it is pictorial cannot be determined by reading the article. Because the study was conducted by simulation we suspect that a simulated external environment was never presented to the subject pilots and the superiority of the display arises not so much from the simultaneous apprehension of external and display events nor from the fact that the two are in registry but simply from the fact that the display was pictorial - the presentation of many dimensions in a common frame of reference. That this is likely the case is supported by the authors own statements.

"The results of the postexperiment interviews with the subject pilots indicated unanimous favor for the windshield displays. The source of this preference is the real-world form of the pictorial representation, in a three-dimensional format, which the windshield display presents. One pilot succinctly summarized this feature by saying that the display "gives you a real-world picture in terms that you're used to seeing." In operational terms, the display gave the pilot a quick, clear picture of the situation as a whole. This facilitated the assessment task that is so critical for all-weather landing irrespective of the mode of control (automatic or manual). As one subject put it, the display "does not require cross checking other instruments as on the panel to verify the situation. All pertinent information is presented together." The enhanced assessment information facilitated the decision whether to land or go-around and the execution of these maneuvers."

In short the display provides the pilot with hierarchical information encoded pictorially.

From the point of view of human factors, other symbols or information may easily be added without increasing confusion in the display in any of the vertical situation displays. Numbered heading tic marks could be added to the skeletal or contact analog display. Additions may be made provided the frame of reference remains consistent. Altitude and airspeed, for example, cannot meaningfully be portrayed in azimuth elevation coordinates and it would therefore be preferable to place them on the periphery of the display rather than attempt integration by sheer contiguity.

CONTROL OF VELOCITY VECTOR

The skeletal and contact analog flight displays as illustrated here evidence a feature that has considerable merit over and above the simple fact that a great many hierarchical variables are presented in a common frame of reference. The velocity vector is represented on these displays by an aircraft symbol with the intention that this symbol will be perceived as the element to be controlled in the display. It is expected that the pilot will directly control the velocity vector rather than attitude and that except for extreme maneuvers, pitch will be considered only as secondary information, and roll will be used only to make control of the velocity

vector or heading easier. Because changes in the direction of the velocity vector follows changes in attitude with appreciable lags, stable manual control will result only if the displayed velocity vector indication is suitably quickened. (For certain aircraft a sudden increase in pitch - and consequently angle of attack - actually results in a rapid drag increase accompanied by a transient loss of altitude, and since this effect results in a momentary change in the velocity vector in the direction opposite to that expected by the pilot, it must be compensated for to avoid instability of control).

The correct null display position for the velocity vector symbol will depend on the particular mission segment being flown. In the case of landing, the symbol will be "flown" to the runway, carrier threshold, or to the symbol representing the centerline-glide slope. In either case a pursuit task is involved with all of its concomitant advantages. In addition, symbols representing the prediction of the rate at which the az-el is changing are provided in order to improve "tracking" performance and allow a smooth asymptotic approach to the desired null position.

HEAD-UP DISPLAYS

Flight Displays

Pictorial displays for head-up (HUD) application have been proposed that vary in function from the display of flight information to the display of raw sensor information. The presumed advantage of the HUD is that it allows the pilot to keep his head out of the cockpit during maneuvers close to the ground - low level flight and landing - thus facilitating the problem of transition from instrument to contact flight. This presumed advantage follows from two observed facts.

- 1) HUD displays are collimated, and thus the pilot does not have to change eye accommodation when shifting his gaze from the display to the outside world.
- 2) HUD displays are in the normal line of sight the pilot uses during contact flight, thus reducing scan time.

Suppose however that one were simply to take information as it is presented on standard instrumentation and project it on a HUD display? The advantages of reduced scan time and reduced accommodation time would still remain with such a configuration, but it is extremely doubtful that this would represent a marked improvement in aircraft instrumentation.

Understandably enough, however, pictorial methods of encoding information have evolved concomitantly with the development of HUD displays. Suggested pictorial HUD displays are similar in choice of coordinate system and symbology with what we have called skeletal pictorial displays. The real reason for the advantage of the HUD, if it turns out that there is one, may be not that the display is mounted in a see-through position over the panel but that the displayed information is encoded pictorially in an easily assimilated fashion.

Because pictorial HUD's replicate in the abstract certain features of the seen physical world it is desirable that the symbols representing those features and the referent objects be in registry. If this requirement is met then the HUD has the marked advantage of permitting the pilot to check the performance of the display system by matching display elements against their counterparts in the external world.

The brightness and form of the symbols on a HUD must be chosen with considerable care for if the symbols are too bright they constitute a veiling illuminance that would tend to obscure ground objects, and if they are similar in configuration to ground patterns — e. g. , runway lights — they may cause confusion. Confusion can be prevented by intelligent choice of symbology and veiling can be avoided by manual or automatic control of display brightness.

A more serious problem arises from the necessity of placing the HUD over the instrument panel of the aircraft coupled with the limited field of view of most HUD devices. In a collimated HUD display where the presentation is to be in registry with the external environment, the cockpit geometry may not allow the pilot to see what he wants to see, for example, the outside

runway, precisely at the time when the reason for using the HUD in the first place occurs. When the display magnification is unity and the angle of attack is large, in many aircraft all pertinent information disappears off the bottom of the display because of the limited field of view of the display. If the image is compressed (magnification < unity) then the symbols in the HUD will be markedly out of registry with objects in the real world and will make a different movement "gain". The effects of this are not completely known, but one hesitates to suggest a departure from unit magnification without empirical evidence.

The effects of small registry errors in collimated displays are deemed minor because in attempting a transition the display symbols will be used by the pilot to tell him where to look. If he is not attempting a transition and is flying the HUD, misregistration will not matter. If the image is not collimated then serious misregistration problems would ensue, and it would be necessary to pick off signals from the pilot's head position to correct the display image. This is not envisioned as a serious issue since collimation appears to be an adequate yet simple solution.

Obstacle Warning Displays

The advent of sophisticated sensors like the laser allow us to entertain the possibility of presenting to the pilot information that he needs but does not now have. In addition to the head-up displays already discussed which deal with familiar categories of information, the complete utilization of helicopters and other vertical rising aircraft requires display of information about the presence of wires and similar obstacles — particularly during landing and take-off.

Operationally a "wire" should be considered as any long, slender object, whether metallic or non-metallic, that is suspended in such a manner as to be spatially detached from its surrounding visible background. A wire lying on the ground or strung along the side of a building does not constitute a hazard to an aircraft in the present context.

Under any flight condition, a critical problem associated with low flight altitudes is the dangerously high probability of striking wires. The problem is most critical under daylight, clear weather conditions. This is true because: 1) the majority of flights are made under such conditions and 2) lower flight altitudes are maintained under these conditions than at night or in bad weather. Thus the highest priority is assigned to the solution of the problem of detecting, discriminating, and localizing wires under daylight, clear weather conditions. A high but secondary priority is assigned to the night, clear weather case.

The problem is difficult because, even under the best conditions of visibility, wires may not be readily detectable by the human eye due to sun angle or the visual background against which they must be discriminated. Under such circumstances the background discrimination problem is clearly the central issue. Under other circumstances wires may be clearly visible to the pilot yet may go unnoticed because his attention is directed elsewhere as required in the performance of other duties.

Thus it is evident that the solution to the problem implies, first, the provision of an alerting function to notify the crew of the presence of wires along the flight path of the aircraft, and second, the provision of a localizing function to allow a determination by the crew of the proper evasive action.

It should be noted that the first item just listed is an absolute requirement if a wire avoidance system is to work at all. The second item, while required if an optimum flight path is to be selected, would not be an absolute requirement if certain operational compromises could be tolerated. For example, if a system simply alerted the crew to the presence of a wire along the projected flight path, then a standard flight procedure could be adopted to avoid collision with the wire, namely: climb until the presence of a wire is no longer indicated. While such a procedure would always avoid collision with wires strung laterally, it would not necessarily avoid a wire suspended vertically, in which case a turn rather than a climb would be appropriate. In any case, a system requiring a standard evasive flight maneuver would be most unattractive operationally. Consequently, the location as well as the presence of a wire must be considered a critical item of information.

When operating under flight conditions in which wire strikes are probable, the visual attention of the crew member flying the aircraft is typically concentrated on the outside world rather than the cockpit instrument panel. Consequently, the indication of the presence of a wire should be one that is virtually certain to attract his attention under this typical condition. Either a highly distinctive and compelling auditory signal or a flashing light presented in the forward external visual field would serve this purpose, and possibly a combination of both is warranted.

The presentation of a suitable indication of the location of the wire causing the alarm is more difficult. For an all-weather system this information would necessarily have to be presented by some type of synthetic display showing at least the range, bearing, and elevation of the wire relative to some meaningful reference, ideally the aircraft's flight path and the surrounding terrain. However, for a system optimized for clear weather, daylight operation the indication ideally should be one that directs the pilot's attention to the location of the real wire in the outside world. This would maximize his chances of selecting the optimum evasive flight path relative to the surrounding terrain and would normally give him an excellent chance of actually seeing the wire, thereby confirming the validity of the alarm. There is of course the possibility that he might not see the wire and conclude that the system gave a false alarm when in fact it did not. (In all cases an evasive action should be taken even though the alarm cannot be confirmed visually, assuming that the system's natural false alarm rate is acceptably low.)

Since the primary objective is to provide a system for clear weather, daylight operation, an extremely simple means of directing the observer's attention to the location of the real wire in the outside world is suggested. Hopefully, this presentation would prove reasonably effective on a clear night, although its effectiveness would surely be extremely limited under conditions of poor outside visibility.

The suggested display is a collimated windscreen or combining-glass presentation showing two symbols: 1) a circle whose diameter and position define the outside field of view being scanned by the sensor, and 2) a second, smaller circle whose position indicates the angular bearing and elevation of the detected wire within the scanned field of view and whose variable diameter is inversely proportional to the range of the detected wire. The large reference circle is presented at all times; the wire-locating circle only when a wire has been detected by the system (see Figure 23).

By means of this presentation the observer's visual attention will be directed toward the detected wire, and the variable diameter of the circle will provide a semi-pictorial, analog indication of how far ahead to look for the wire, a small circle indicating that the wire is at a relatively great distance. The increasing diameter of the circle will represent the reduction in range as the aircraft approaches the wire.

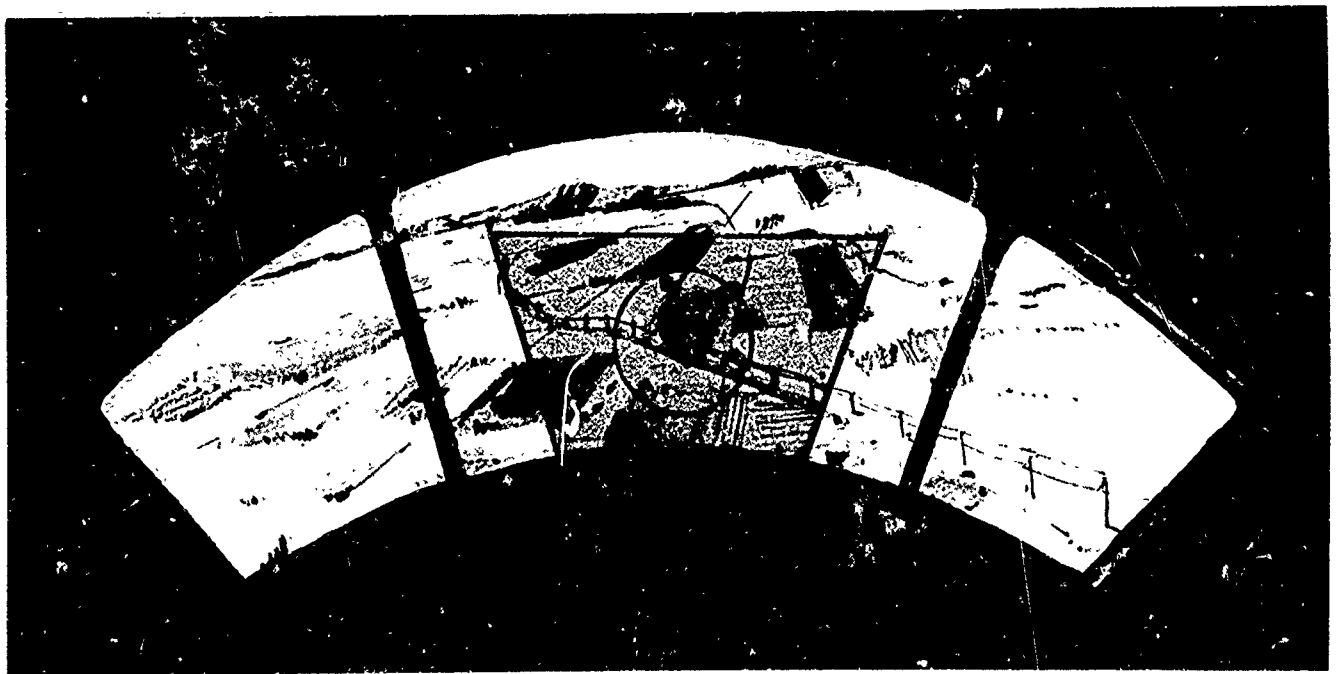


Figure 23. Artist's conception of wire-locating display. Two circles are optically projected onto a combining glass and collimated to appear against the outside background. The larger circle defines the laser beam's scan cone. The smaller circle shows the position of the nearest wire, and its diameter is inversely proportional to range.

This concept, of course, remains completely unevaluated and an empirical evaluation must precede acceptance. There is no reason why this kind of information cannot be incorporated as an integral part of any pictorial VSD for the coordinate system is compatible and only the question of suitable symbol coding needs to be resolved.

HORIZONTAL SITUATION PICTORIAL DISPLAYS

The concepts that led to the requirements for map displays are much more familiar than is the rationale for the vertical pictorial display. The need for such displays has been recognized for years, and what remains to be worked out in these displays are detail questions of chart content, scale and the like as well as engineering problems of weight, space, cost, and mechanization.

It will be taken as self evident that map displays are desirable and a detailed review of data supporting this position will be omitted. We will discuss the applications for HSD displays as well as some of the problems associated with establishing the requirements for these displays. The emphasis will be placed on the map display used for navigation although it should be recognized that the HSD is not solely a navigation display but may be used to display any information that can be stored and scanned out.

DISPLAY FUNCTIONS

Optical moving-map displays were conceived in 1949 as a superior means of presenting the aircraft position information made available by the new rho-theta radio navigation system then known as DME-Omni. Laboratory simulation experiments at the University of Illinois Aviation Psychology Laboratory and flight evaluations of experimental units by the former CAA during the early 1950s confirmed the optimistic hopes of the inventors and proponents.

In all of these tests no pilot ever became lost while flying with a map display. Private pilots and even non-pilots using map displays could navigate as well as experienced instrument pilots using conventional instruments. Perhaps even more surprising was the finding that pilots controlled airspeed, altitude, attitude, and heading significantly better under IFR conditions when using a map display, presumably because less attention was required for navigation tasks. This finding might also be interpreted as evidence supporting the concept of the hierarchical nature of the pilot's task since a map display presents information concerning the higher order sub-goals of flight suitable for establishing lower order indices of desired performance such as heading, altitude, and speed.

The capability of using the HSD for display of stored information to show self test routines and to provide a means for the crew to talk to an on-board computer was exploited in the map display and associated controls of the ASG-18 fire control and navigation system. The use of the map display for the manual insertion of aircraft, target, destination, and TACAN station position coordinates has proved to be a simple and effective way for the crew to talk to the ASG-18 system in flight.

The greatest single aid an operator can have in interpreting a radar ground map is knowing what he is looking at or, more precisely, the relative position of what he is looking for. Such knowledge can be achieved through intensive pre-flight study of charts, aerial photographs, radar imagery, etc., or by inflight reference to such materials. An effective aid for utilizing the radar is to present on a moving-map display the relative positions of the principal surface objects that should be visible and identifiable on the radar display. While a great deal of improvement in charting techniques is required to take full advantage of this mode of operation, impressive progress is being made by the USAF Aeronautical Chart and Information Center and the Navy's Oceanographic Office.

In tactical aircraft, the value of a moving-map display as a primary cockpit navigation device is greatest when flying devious routes at extremely low altitudes. Under such circumstances, the range of visibility is severely limited even under ideal weather conditions. Even a slight

departure from a pre-planned flight path can result in a missed checkpoint and possibly a disoriented crew. With the highly accurate self-contained navigation sensors now available, pre-planned point-to-point navigation is effective with standard flight instruments, but far greater tactical flexibility is afforded if the outputs of such sensors are presented directly to the crew in terms of continuous, instantaneous position on a moving-map display.

Thus, the display of stored information, used in conjunction with appropriate cockpit controls, appears to be a most effective device developed to date to assist an aircrew in performing the following functions:

- 1) Low-altitude tactical navigation, particularly at night or in poor weather and when departures from pre-planned routes are advantageous or required.
- 2) Interpretation of surface-mapping radar or other high-resolution, real-time, imagery-producing sensors.
- 3) Updating self-contained navigation systems by reference either to visual or radar position fixing.
- 4) Initiating and interpreting in-flight system self-test routines or performing the same tests on the ground.

In addition to these four principal functions a number of incidental functions may be provided at little cost. Among these are the display of check lists and other procedural instructions, maintenance information, and terminal area traffic procedure diagrams.

The types of data that must be presented represent two distinct classes. The first class consists of relatively unchanging long-lead-time materials such as map presentations of theater areas, terminal areas, and aircraft and test procedures. The second class consists of tactical data which requires a quick reaction-time capability if it is to serve as a truly useful mission aid. Items such as current data on defensive deployments in tactical areas and readily available display of alternate attack and departure corridors offer a potential for invaluable assistance to the

combat crew. This means a requirement for a storage capacity sufficient to hold the unchanging items and a technique that permits daily changes in the stored material.

If the map display is to be most effective as a flight instrument or as an instrument for assisting the operator in the interpretation of high-resolution imagery from real-time surface-mapping sensors used in locating targets and navigation checkpoints, then the map presentation must be oriented relative to the aircraft's flight path or heading. When the momentary function of the display is to present alphanumeric information such as radio frequencies, runway headings, place names, or terrain elevations, then it is equally important that the printing be right side up to minimize operator reading errors. These combined requirements call for a dual mode of presentation providing either course-up or north-up map orientation.

For similar reasons, both automatic and manual chart selection and positioning are required as are many other operating features contributing to the general goal of extreme flexibility.

MAP DISPLAYS

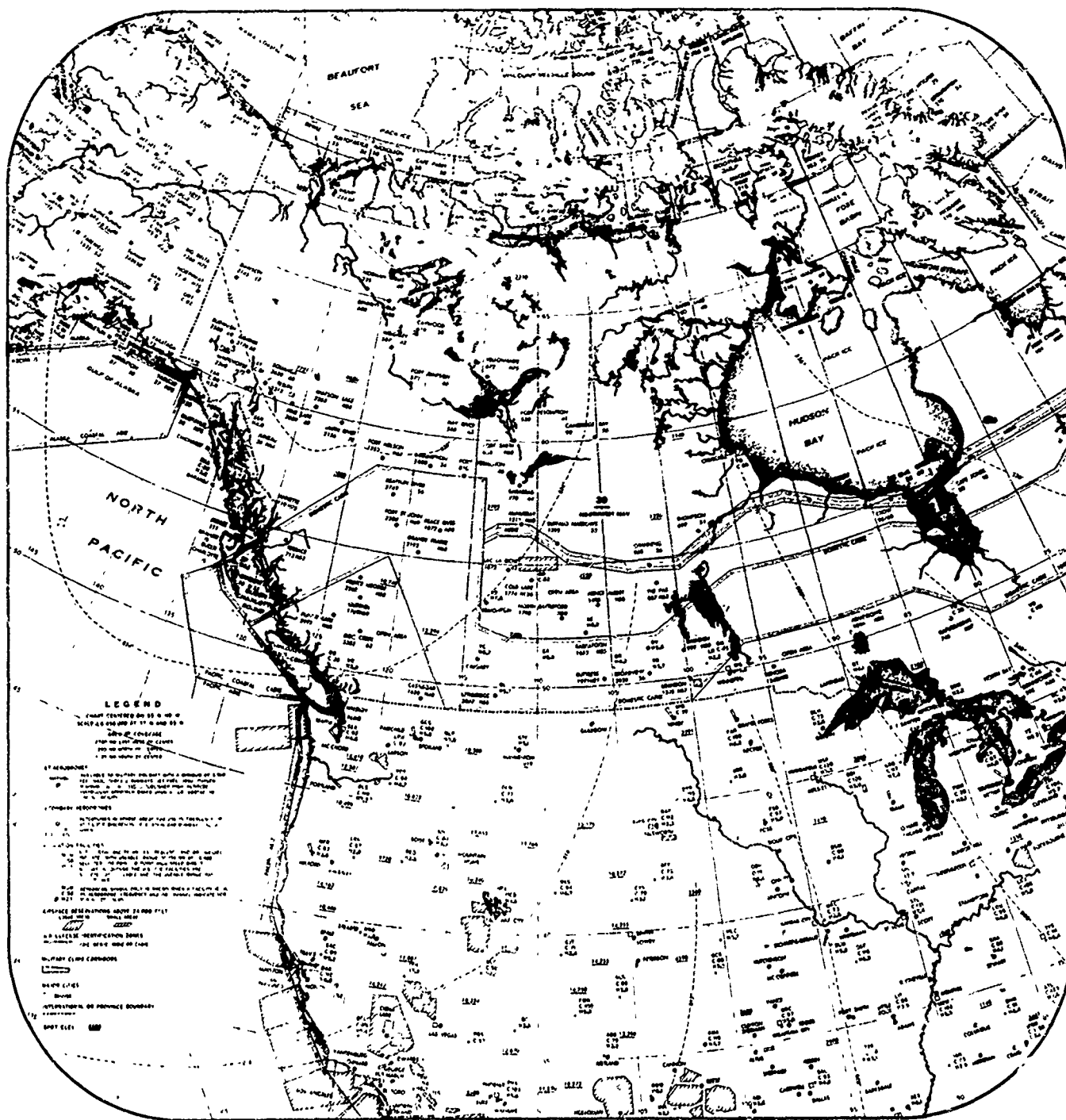
If the display is used primarily as a map, the main issues involve: 1) what shall be represented — the information required — and 2) the method of encoding it. The derivation of these requirements is highly mission dependent as the great variety of maps evolved over the past several centuries will attest, and the cartography must be tailored to satisfy the decisions required of the user.

The optimum characteristics for electronically generated or optically projected charts differ greatly from those for charts printed on paper. These differences warrant the preparation of special charts. Optimum charts for optical projection in the cockpit environment and for use in tactical operations differ from conventional flight charts in content, symbology, scale, print size, contrast, and color.

To be most effective the charts should be relatively uncluttered, bold in their lettering and other symbology, and of high resolution and contrast. Charts of at least two different scales should be provided: one to a relatively gross scale for enroute navigation and the other to a scale approximately four or five times as fine for local area operations such as position fixing, weapon delivery, traffic control, and landing. Each type should contain only information related specifically to its intended operational use, to avoid cluttering the chart and allow the use of a bold format. A single master chart to a third scale encompassing the entire operational area and showing the location and identity of all charts available in the display is also highly desirable. Examples of charts meeting these requirements are shown in Figures 24 through 26.

Map displays create the greatest single source of light generated within the cockpit at night, even when dimmed to the same level as other displays. The total luminous flux emitted by the display can be reduced at least an order of magnitude by the use of negative black and white charts (white figures on a black background). This type of presentation can also be used with particular advantage in conjunction with color coded dynamic symbols.

There are some classic problems in map displays. Should the map move or should the symbol representing ownship move? The answers to such questions are much discussed rather than resolved in the literature, and the conflicting points of view will not be belabored here. Suffice to say that the heading-up, north-up issue is best resolved by considering whether the pilot is using the display for planning, and consults it only infrequently, or is using it as a corollary flight instrument, in which case the display dynamics are important. It should also be mentioned that the HSD cannot be considered in isolation - particularly with respect to its motion - but must be designed to sensibly fit in with the other cockpit displays.



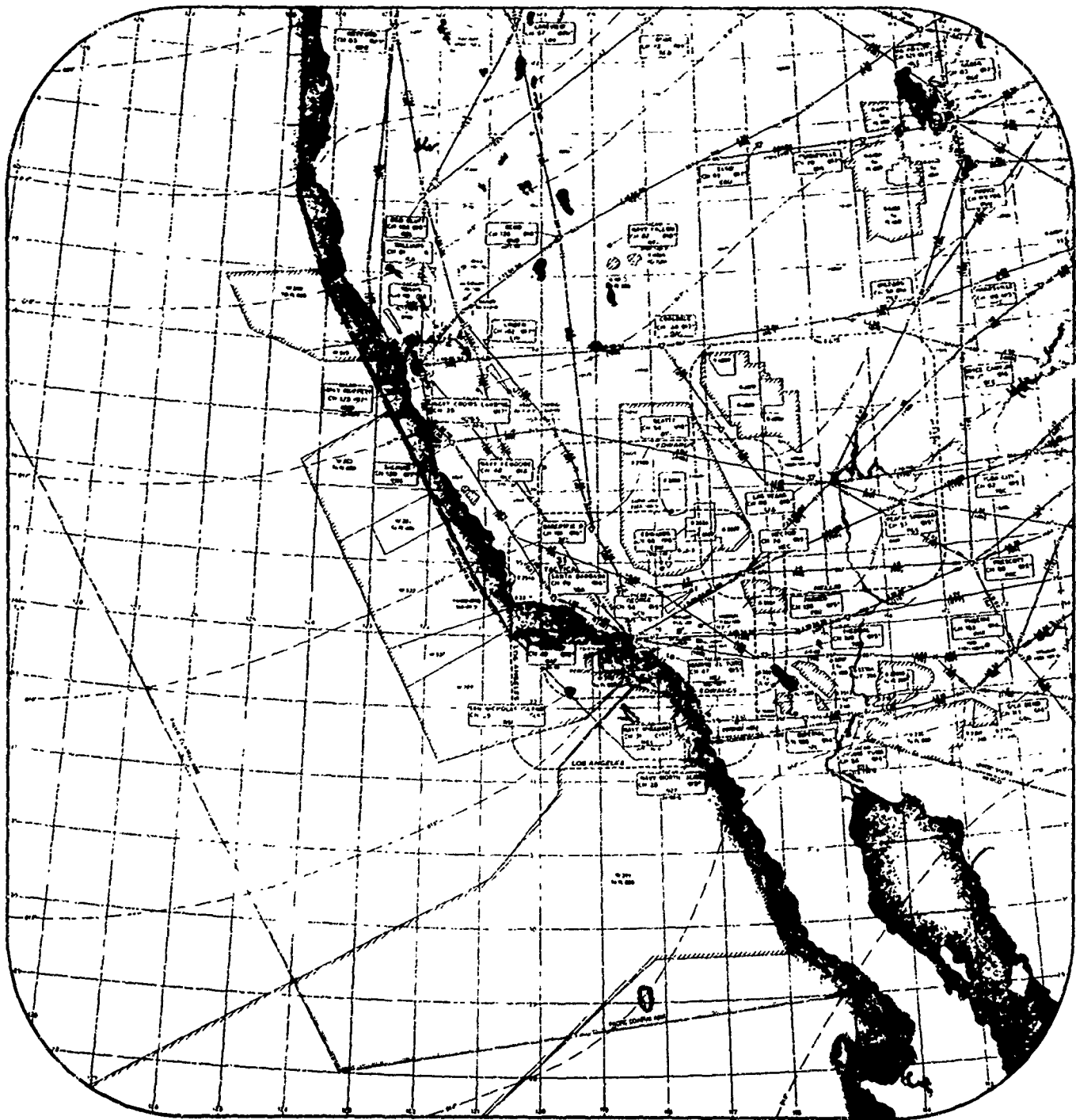


Figure 25. Cartography, Navigation
(Not to True Scale)

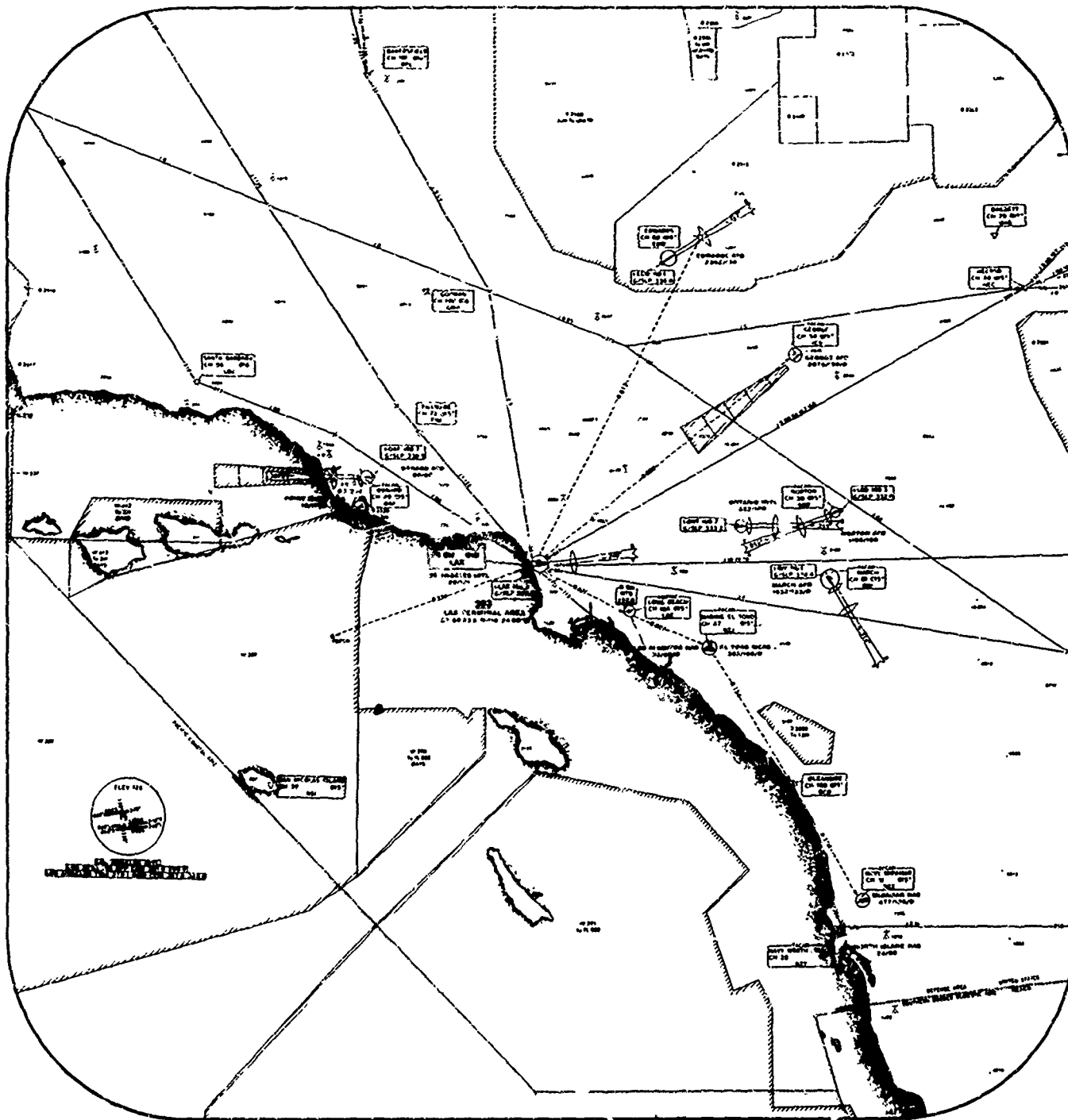


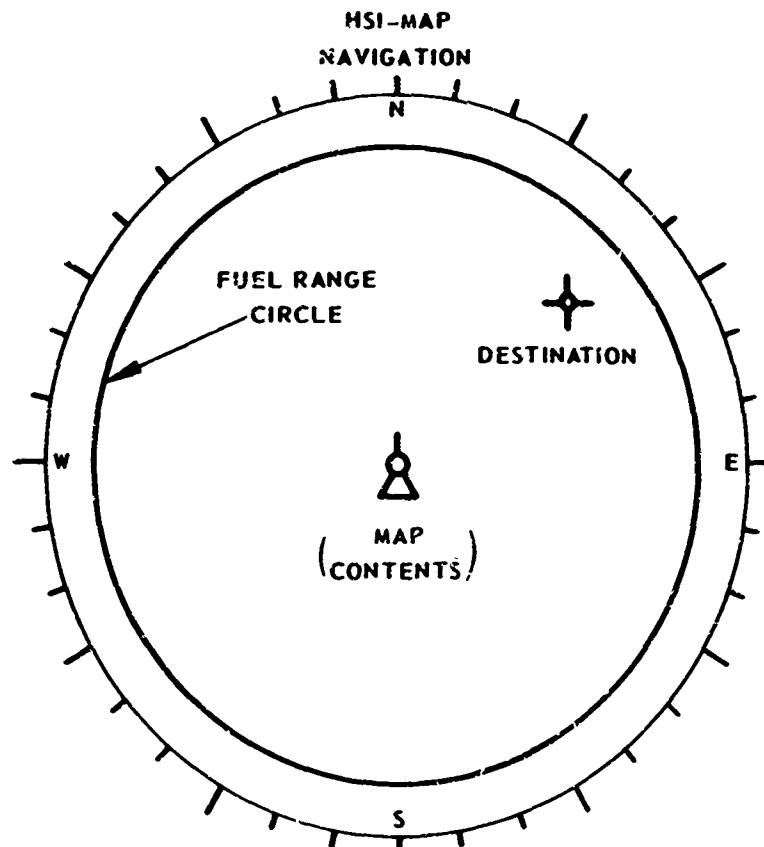
Figure 26. Cartography, Terminal
(Not to True Scale)

The updating requirements for a map-type display will also vary with the use to which the display is put. If the area displayed is large and the map is used primarily for en route point-to-point navigation, the information need only be updated infrequently. If conversely, the area displayed is small, for example, a few hundred yards showing the location of several helicopter landing pads during a helicopter landing maneuver, then the map display is really a corollary flight instrument, as was mentioned earlier, and the information needs to be updated at a frequency related to the frequency with which events are changing or, as a minimum, at a rate approximating the pilot's response rate. A series of sketches illustrating some desirable characteristics of map displays for fixed wing and helicopter aircraft is shown in Figures 27 through 31.

The object of the map displays illustrated in the sketches is to provide the operator with a representation of the geographic relationship of significant objects in relation to his own ship in order to permit the pilot to maintain continuous geographic orientation. Coverage, scale factor, and display size were evolved from a joint consideration of vehicle speed, vehicle kinematics, area useful for planning, cockpit size, and display resolution. Chart content density is not specified but will be a compromise between the need for a great deal of cartographic information and the fact that clutter will obscure it. Representative chart contents for high speed aircraft were shown in Figures 24, 25, 26. Accuracy and scale factor requirements were derived from estimates of the operational requirements for positioning along with the necessity that the transition from one scale to the other in the landing condition be carried out without fuss. Representative values for these variables are shown in the sketches. The "hover lines" shown in Figure 31 are taken from Lukso and Fellingner (1965).

The displays illustrated are intended for use in navigation, and the design principles used derived from considerations of guidance and control as well as from a consideration of the pilot's hierarchical tasks.

HIGH SPEED AIRCRAFT

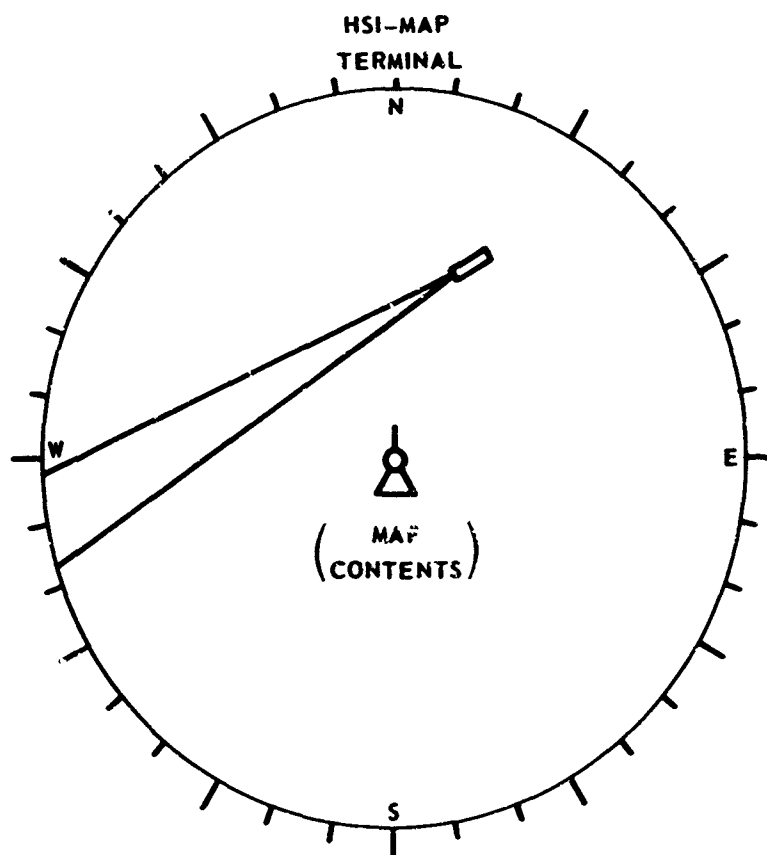


DISPLAY SIZE = 8 in.
VIEWING DISTANCE = 28 in.
SCALE FACTOR = 30 N MI/in
DISPLAY COVERAGE = 240 N MI
MOTION RELATIONSHIP = OPTIONAL

SYMBOLS	
1. OWNERSHIP POSITION TO 26 N MI AT 30°	3. OWNERSHIP TRACK
2. OWNERSHIP HEADING	4. DESTINATION POSITION
	5. FUEL-RANGE LOCUS
CHART CONTENTS	
HIGH ALTITUDE	LOW ALTITUDE
1. LAND AND WATER MASS 2. LOCATION AND IDENTIFICATION OF NAV AIDS 3. LOCATION AND IDENTIFICATION OF AIRDROMES 4. LOCATION AND ELEVATION OF PEAK ALTITUDES 5. LOCATION AND IDENTIFICATION OF RESERVED AIRSPACE 6. AIR DEFENSE ZONES 7. LATITUDE AND LONGITUDE LINES 8. INTERNATIONAL BOUNDARIES 9. ISOGONIC LINES	1. LAND AND WATER MASS 2. ELEVATION AND TERRAIN FEATURES 3. DEFENSE INSTALLATIONS 4. TARGETS AND CHECKPOINTS 5. LANDMARKS 6. POLITICAL BOUNDARIES 7. LATITUDE AND LONGITUDE

Figure 27. Map Display, Navigation

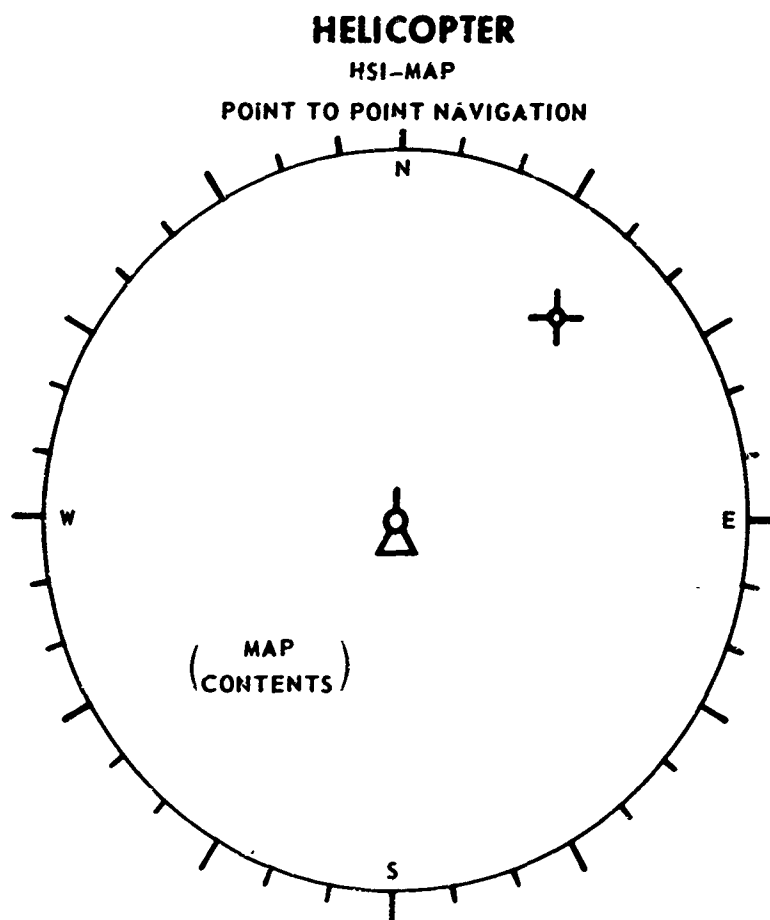
HIGH SPEED AIRCRAFT



DISPLAY SIZE = 8 in.
 SCALE FACTOR = 3 N MI / in.
 DISPLAY COVERAGE = 24 N MI
 MOTION RELATIONSHIP = OPTIONAL

CHART CONTENTS	<ol style="list-style-type: none"> 1. AIRDROME, CARRIER, OR RUNWAY INFORMATION 2. NAV AIDS 3. APPROACH PATTERNS AND DATA 4. OBSTACLES 5. LAND AND WATER MASSES
SYMBOLS	<ol style="list-style-type: none"> 1. OWNERSHIP POSITION TO 0.25 AT 3σ 2. OWNERSHIP HEADING 3. DESTINATION POSITION 4. RUNWAY OR CARRIER HEADING

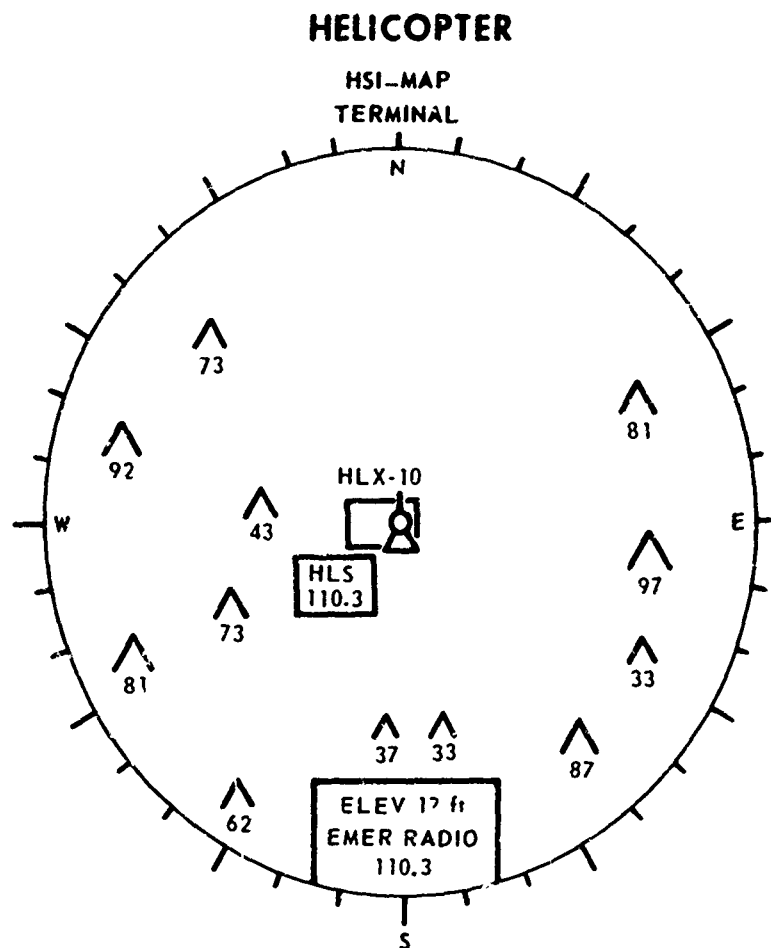
Figure 28. Map Display, Fixed Wing, Terminal



DISPLAY SIZE = 8 in.
VIEW DISTANCE = 28 in.
DISPLAY COVERAGE = 48 N MI
SCALE FACTOR = 6 N MI/in.
MOTION RELATIONSHIP = OPTIONAL

CHART CONTENTS	<ol style="list-style-type: none"> 1. LATITUDE AND LONGITUDE 2. AIRDROMES OR LANDING FACILITIES 3. LOCATION AND ELEVATION OF HIGH POINTS 4. LOCATION AND IDENTIFICATION OF ELECTRONIC AIDS 5. LOCATION AND IDENTIFICATION OF DEFENDED POINTS 6. LOCATION AND IDENTIFICATION OF RESTRICTED ZONES 7. INTERNATIONAL BOUNDARIES 8. UNIQUE TOPOGRAPHIC FEATURES
SYMBOLS	<ol style="list-style-type: none"> 1. POSITION OF OWNSHIP TO $\pm \frac{1}{2}$ N MI AT 3σ 2. HEADING OF OWNSHIP 3. POSITION OF DESTINATION TO $\pm \frac{1}{2}$ N MI AT 3σ 4. FUEL RANGE LOCUS 5. OWNSHIP TRACK

Figure 29. Map Display, Navigation



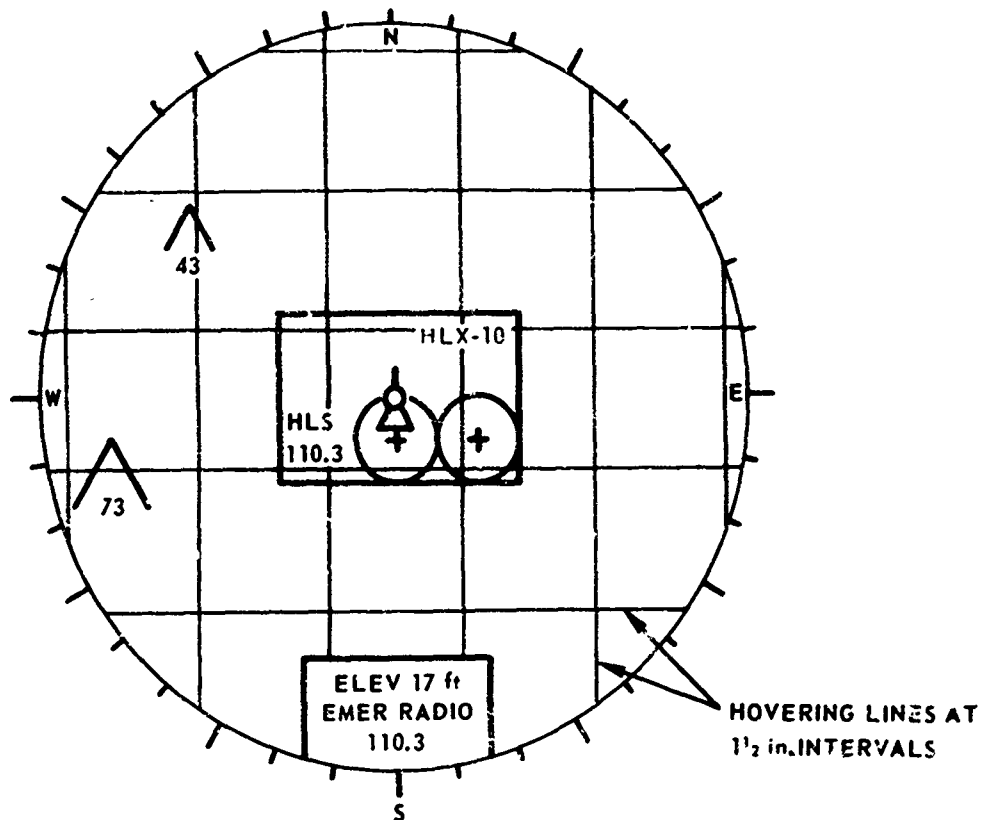
DISPLAY SIZE = 8 in.
VIEW DISTANCE = 28 in.
DISPLAY COVERAGE = 40,000 ft
SCALE FACTOR = 5000 ft/in.
MOTION RELATIONSHIP = MOVING MAP

CHART CONTENTS	1. LOCATION AND IDENTIFICATION OF TERMINAL FACILITY 2. LOCATION AND ELEVATION OF OBSTRUCTIONS 3. LOCATION AND IDENTIFICATION OF ELECTRONIC NAV AID 4. FIELD ELEVATION 5. RADIO FREQUENCIES 6. UNIQUE TOPOGRAPHIC FEATURES
SYMBOLS	1. POSITION OF OWNERSHIP TO 500 ft AT 30 2. HEADING OF OWNERSHIP 3. OWNERSHIP TRACK

Figure 30. Map Display, Terminal

HELICOPTER

HSI-MAP
APPROACH, LANDING, DEPARTURE



DISPLAY SIZE = 8 in.
VIEW DISTANCE = 28 in.
DISPLAY COVERAGE = 2000 ft
SCALE FACTOR = 250 ft/in.
MOTION RELATIONSHIP = MOVING MAP

CHART CONTENTS	<ol style="list-style-type: none"> 1. LOCATION AND IDENTIFICATION OF TERMINAL FACILITY 2. LOCATION OF LANDING AREA WITHIN TERMINAL FACILITY 3. LOCATION AND ELEVATION OF OBSTRUCTIONS 4. LOCATION AND IDENTIFICATION OF ELECTRONIC NAV AID 5. FIELD ELEVATION 6. RADIO CHANNEL FREQUENCIES 7. UNIQUE TOPOGRAPHIC FEATURES
SYMBOLS	<ol style="list-style-type: none"> 1. POSITION OF OWNERSHIP RELATIVE TO PAD TO ± 32 ft AT 30° 2. HEADING OF OWNERSHIP
HOVERING LINES	<ol style="list-style-type: none"> 1. LATERAL VELOCITY RELATIVE TO GROUND 2. FORWARD VELOCITY RELATIVE TO GROUND

Figure 31. Map Display, Landing

SENSOR DISPLAYS

Operational Applications

There is a class of pictorial displays that does not fall under the rubric of the map or flight control displays as illustrated in the prior sections of this report. These are the literal pictorial displays that are the direct output of sensors and are not so easy to illustrate with simple sketches. The primary application for such displays, in the mission segments under study, is in navigation and related tasks, although the same displays may also be used for such tasks as target acquisition and weapon delivery.

If the terminal or waypoint goal is stated as a geographic location, it is evident that means must be provided for the pilot to realize his position with respect to it. This is the central problem in navigation: to determine where one is with respect to where one wants to go. In a map display the pilot could accept as true the output of a navigation system as it is reflected in the display only at the peril of error as large as the accumulated navigation error.

In inertial systems it is customary to update position periodically in order to prevent the accumulation of large errors. One technique for updating is to identify a landmark whose position is known, measure ownship position with respect to the landmark, and insert this information in the navigation computer. The identification process may be carried out by an operator using a literal pictorial display of information gathered by a pattern sensor such as radar, TV, or IR. Such pictorial displays need not have all the properties required in the hierarchical displays for they are not used to direct the vehicle toward a goal but only to identify a "target."

The requirements for these displays, then, will not necessarily be based on the principle of replicating the pilot's goal hierarchy, but will be couched in terms meaningful for the human recognition process when the task is solely recognition or a type of "matching." If the task is truly a matching task then means must be provided for the operator to

correlate stored with raw data. There are several ways to do this. One is to store prepared imagery in the HSD magazine, call it up when the navigation system thinks the time has arrived (or on demand), and compare the stored imagery with imagery originating with a live sensor in order to identify checkpoints or objects whose coordinates are known. Another technique might be to assign a symbol to each class of landmark, store the coordinates of each item in each class, then superpose the symbols on the raw data display in accordance with navigation system prediction. If such a display is monitored rather continuously, then the operator's task is historical, and errors can be detected as they grow rather than in discrete steps when each object must be identified in a non-historical context.

In addition to using a literal sensor display to update the navigation system by searching for and recognizing predetermined checkpoints, a high resolution radar system, for example, may be used to select a helicopter landing spot. Deferring for the moment questions of weight, size, and cost, it seems clear from an examination of the output of radars with a high resolution that such devices could, in favorable circumstances, be used to select a clearing in the jungle or to aid in flying the nap of the earth in helicopter operations. These radars, operated optimally, allow one to pick out cleared from wooded areas and even to discriminate individual trees. Such capability is a comparatively recent development and certainly increases the potential of such radars for this application.

In helicopter operations the procedure might be to pop up, take a radar snapshot, descend and examine the radar output. If the image were stored, rectified, and scaled, it could be used directly in place of the map display on the HSD. Or, as at least the center position of the image is known, it could be used simply to update position in the computer or to mark a coordinate position in the computer and thus on the display. In either case, the radar allows one to tie the system to the real world of things and obstacles rather than the abstract world of inertial space.

The operational utility of all such sensor displays depends on the observer's ability to recognize targets or checkpoints. This is such a critical problem that an examination of what is entailed is warranted.

Target and Checkpoint Recognition

Because most tactical aircraft of the future will have on board elaborate avionics systems that will include pattern sensors like radar, IR, and TV, one must consider the conditions under which targets or objects can be recognized through the medium of these sensor systems.

This discussion is intended to provide information helpful to the design of such sensor systems with particular reference to pictorial displays that provide the basis for target or landmark recognition by the crew. In addition, a few of the operational variables not subject to design maneuver but critical for the operation of the system will be discussed.

A complete review of all the purportedly relevant data on target recognition would be too voluminous for this report. For the most part the target recognition literature is a compound of unrelated studies dealing with theoretical rather than practical issues and using abstract rather than realistic imagery. Rather than attempt a generalization based on these academic studies we have elected to lean heavily on both our own experience and the data reported from a few select studies that have utilized realistic imagery in an effort to capture the complexity of an operational situation.

The classification of objects seen in a display is a process of inference based on the target signatures evidenced in the display coupled with the knowledge and skill the operator brings to the situation. The target signatures are many and varied, and the operator's ability to use them is affected by the design characteristics of the system, the operational environment, and his own a priori information. It is in the design characteristics of the system that we are interested and the effects that design characteristics have on performance. Unfortunately, a rigorous quantitative description of the interaction between design characteristics and performance has not been elucidated.

For the sake of clarity and convenience each of the more important characteristics will be discussed separately, but it should always be remembered that the interactions among these variables have a marked but not completely known effect on performance. For example it is likely

that the type briefing and reference material employed should be considered in choosing the optimum resolution or optimum scale. The operational task in a tactical situation is to locate the target or landmark rather than conduct a long involved interpretation of the target imagery. Therefore, the location task may succeed by the crew using either contextual information or by recognition of the target on the grounds of its shape signature.

The appropriate tactic will depend on both the location accuracy required and the a priori information available. If the target position is known exactly and if the reference material indicates that the target can be located by its position with respect to a unique configuration of conspicuous landmarks --- rivers, roads, etc. --- then it is expected that the scale which affords a large context would be relatively more important than resolution. If, on the other hand, the position of the target is not known precisely and the target must be located and identified on the grounds of its shape signature, then resolution would assume great importance, and the appropriate scale would be that scale which, when coupled with the required resolution, allows the shape signature to be seen with comparative ease. In short, the choice of optimum scale and resolution will depend directly on the kind of a priori information available to the operator.

Resolution

Resolution is perhaps the variable most often mentioned as being critical for improved performance in target recognition. It seems self evident that the finer the resolution the easier it will be to identify a visual object. Attempts to determine the system resolution required for any particular recognition task have occupied investigators for many years and several studies report data that explicitly or implicitly show the effects of resolution on the probability of recognition. (Bennett, Winterstein, Taylor and Kent, 1963; Jennings, Meeker, Praver, and Cook, 1963; MacDonald and Watson, 1956; Steedman and Baker, 1960).

Evidence which allows some quantitative relations to be extracted is reported in the Jennings study conducted at Minneapolis-Honeywell. In this study, the investigators were interested primarily in the effects that ground resolution and contrast have on the observer's ability to identify a variety of military targets using realistic photographic imagery. In the study there was no formal briefing, and there was no attempt to take contextual information out of the imagery so the observers had more than just the shape signature of the target. The observers were shown the imagery and asked to classify the objects they saw by checking items on a list provided. Of particular interest is that they were asked to respond at the level of description that would most completely describe the target. The completeness of their description, (the level of response) depended, of course, on the resolution of the imagery. For example, if the target was in fact a C-54 aircraft, at the lowest level of description the observers might respond by classifying it only as an object, at finer resolution by naming it an aircraft, at a still finer resolution by identifying it as a transport aircraft, and at the finest resolution by calling it a C-54.

Three reporting levels of description were used in the study, and the data are analyzed in terms of description level. A chart taken from the Jennings report which summarizes the data is reproduced in Table VII. The reporting level is indicated in the chart by noting how the target was classified as a function of resolution. For example, a road grader is classified simply as a vehicle with ground resolution of 16-32 feet, as heavy equipment with resolution of 8-16 feet, and as a road grader when the resolution is better than 8 feet. We are interested in generalizing from this data in order to arrive at an estimate of resolution requirements for any target --- not only those listed in the chart. In order to synthesize a principle from this welter of particulars, the first step was to invoke the notion of "definition" which would allow us to make generalized inferences that are divorced from the particular resolutions coupled with the particular targets that were used in the study. "Definition" is defined as the number of resolution elements placed along the major axis of a compact target. A sensor system with a ground resolution of 2 feet looking at a tank 30 feet long exhibits a definition of 15.

TABLE VII. TARGET IDENTIFIABILITY AT VARIOUS LEVELS OF GROUND RESOLUTION

* UNDER SOME CONDITIONS
- NO IDENTIFICATION POSSIBLE
? UNKNOWN

	1 - 2 FEET	2 - 4 FEET	4 - 8 FEET	8 - 16 FEET	16-32 FEET	32-64 FEET
AIRCRAFT	C - 54 L - 20 F - 101 B - 57 B - 52 SM OR MED HELICOPTER	C - 54 L - 20 F - 101 B - 57 B - 52 SM OR MED HELICOPTER	C - 54 L - 20 F - 101 B - 57 B - 52 HELICOPTER	C - 54 UTILITY A C FIGHTER BOMBER B - 52	UTILITY A C - A C A C B - 52 -	? - ? ? B - 52 -
VEHICLES	ROAD GRADER BULL DOZER SEMI & ENCLOSED TLR TANK TRUCK 2 1/2 TON TRUCK JEEP RAILROAD VEHICLE TANK (LIGHT, MED, HEAVY)	ROAD GRADER BULL DOZER SEMI & ENCLOSED TLR TANK TRUCK 2 1/2 TON TRUCK JEEP BOXCAR, FLATCAR, ETC. LT, MED OR Hvy TANK	ROAD GRADER BULL DOZER SEMI & ENCLOSED TLR TANK TRUCK 2 1/2 TON TRUCK SMALL TRUCK BOXCAR, FLATCAR, ETC. TANK	HEAVY EQUIPMENT HEAVY EQUIPMENT LARGE TRUCK VEHICLE LARGE TRUCK VEHICLES RAILROAD VEHICLE TANK	VEHICLE VEHICLE VEHICLE - - - RAILROAD VEHICLE TANK	? ? ? - - - ? ?
WEAPONS	MAN CARRIED WEAPON VEH MOUNTED WEAPON 105 MM & 155 MM REC RIFLE 8" GUN 8" HOWITZER GND LAUNCH MISSILE AIR LAUNCH MISSILE	- 105 OR 155 MM REC RIFLE TOWED WEAPON 8" HOWITZER GND LAUNCH MISSILE AIR LAUNCH MISSILE	- VEHICLE MOUNTED WEAPON - TOWED WEAPON GND LAUNCH MISSILE AIR LAUNCH MISSILE	- - - - TOWED WEAPON - -	- - - - - - -	- - - - - - -
MISCELLANEOUS	TENT (10 MAN & HOSPITAL) JET ENGINE TEST AREA FUEL DUMP AIRFIELD ROAD (IMPROVED) TROOPS RAILROAD TRACKS BRIDGE DAM	TENT JET ENGINE TEST AREA FUEL DUMP AIRFIELD ROAD TROOPS RAILROAD TRACKS BRIDGE DAM	TENT JET ENGINE TEST AREA FUEL DUMP AIRFIELD ROAD - RAILROAD TRACKS BRIDGE DAM	TENT COMPLEX FUEL DUMP AIRFIELD ROAD - - BRIDGE DAM	- COMPLEX FUEL DUMP AIRFIELD ROAD - - BRIDGE DAM	- - FUEL DUMP AIRFIELD ? - - ? DAM

The definition required to identify the targets used in the Jennings study may be calculated by making reasonable estimates of target size along each target major axis. This was done, and Figures 32 through 34 are plots of definition versus probability of recognition for three levels of description for a select group of targets. * The definition values were then averaged across targets, plotted, and the resulting curves are shown in Figure 35.

Although even this averaged data is "noisy" there appears to be a discontinuity in the level II and level III curves; the level III curve breaks at a percent of 30 and the level II at 70. It is evident that some factor other than ground resolution is operating to limit performance to those percent correct values under those conditions. The most probable cause is that at these values the definition as displayed equals the visual acuity limit of the observer so that even though the physical definition improves the observer can resolve no more and at a fixed scale cannot improve his performance. It may be supposed then that the break in the curves is an artifact and if increased definition could be utilized by the observer --- by, for example, changing scale --- the curves would continue in a straight line. It should also be noted that the data used to generate the level I curves are compressed against the 100(99) percent scale on the percent correct axis with the consequence that the averages are markedly skewed. For this and other rational reasons it is felt that this particular average is an anomaly.

*A target was included in this select group if there were differential data at all three levels of description as well as data for at least three resolution values. Thus, if a target, for example a bridge, were recognized as a bridge 1 percent or 100 percent of the time at all resolution values, it was not included because the data provided no differential information. This policy is, of course, susceptible to the argument that we have conveniently rejected all those targets that are not differentially classified at different resolution levels. We recognize the logic of the argument and pass on.

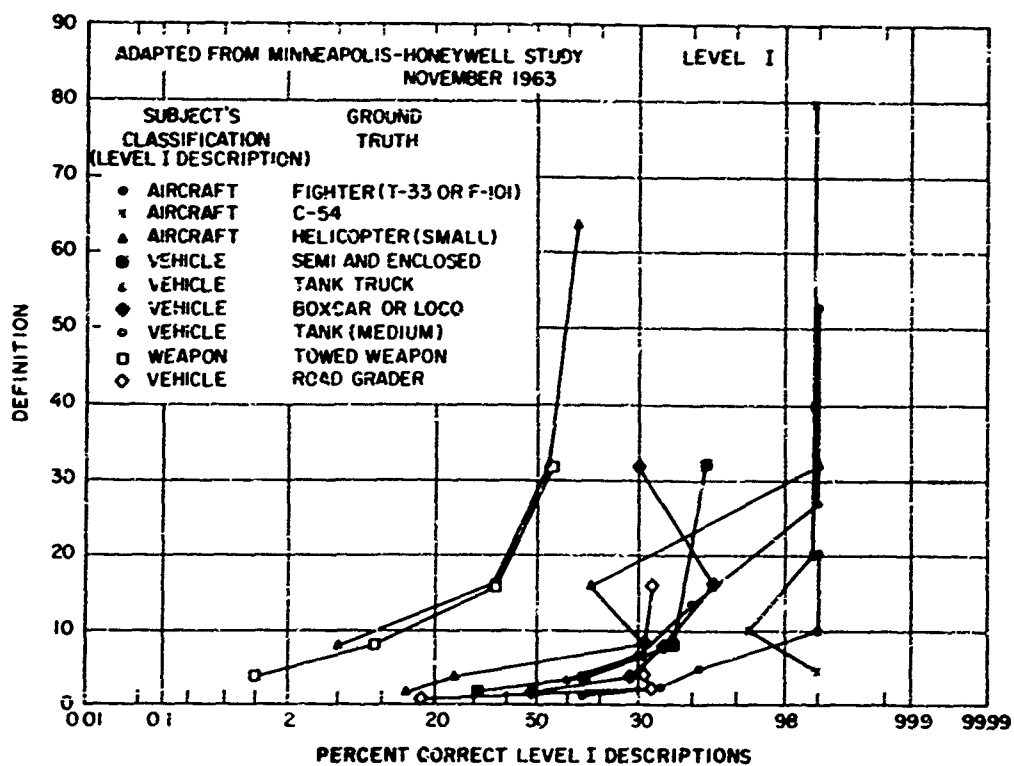


Figure 32. Correct Responses VS Definition for Level I Description

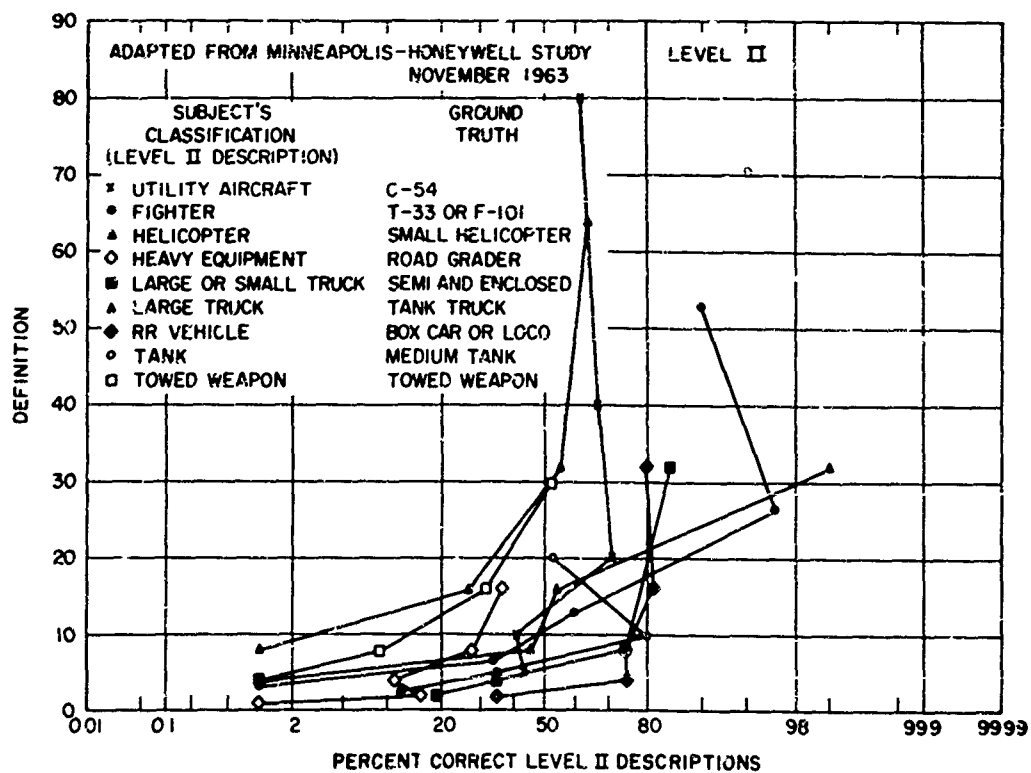


Figure 33. Correct Responses VS Definition for Level II Description

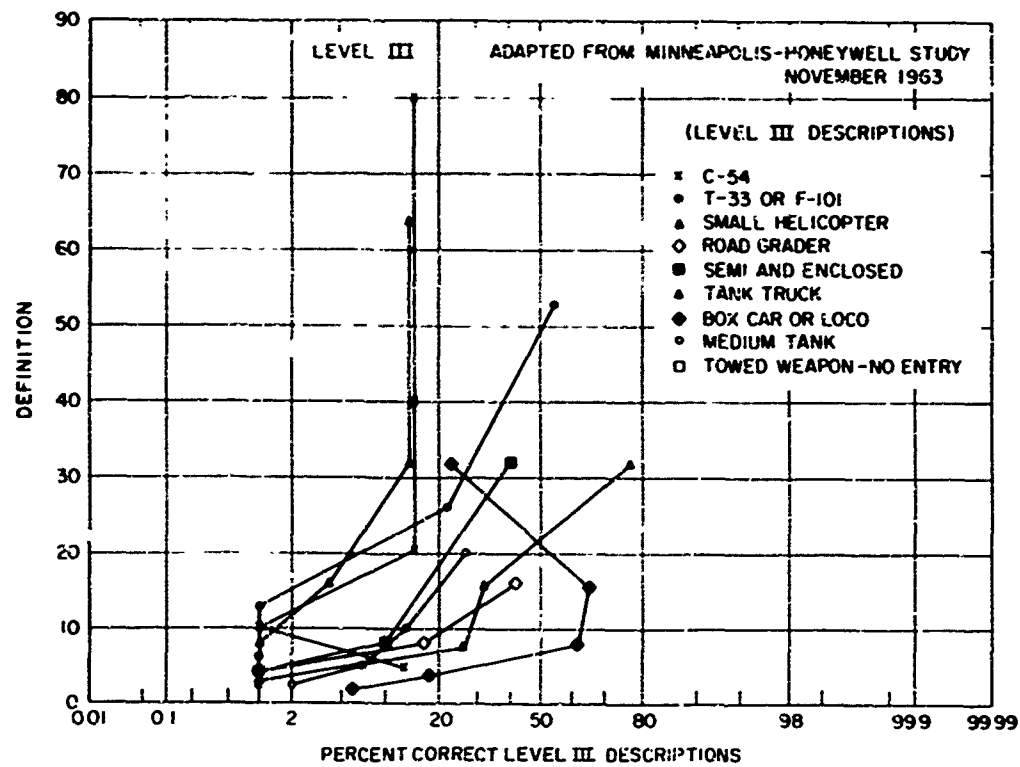


Figure 34. Correct Responses VS Definition for Level III Description

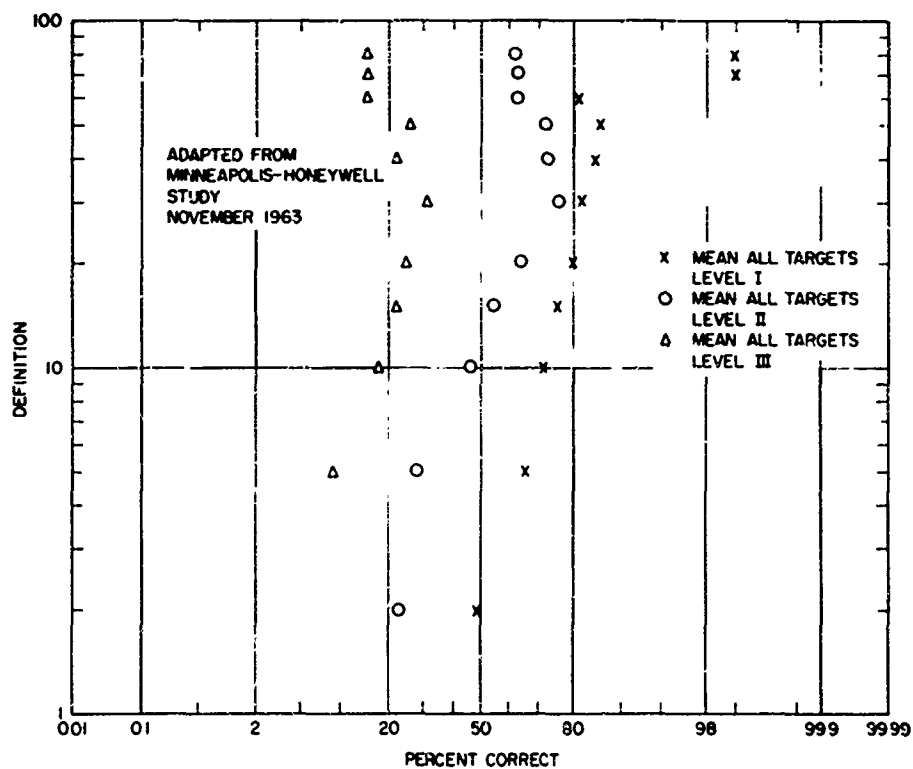


Figure 35. Correct Responses VS Definition Means for Each of Three Levels

The analysis was carried out to this length in order that the curve expressing the relationship between probability of recognition (P_r) and definition could be synthesized. Using these data and compounding them with the old rule of thumb that to go from one level of description to the next requires an increase in resolution by a factor of five, (Space Handbook, 1959, p. 173) one may then construct the graph shown in Figure 36 which purports to show the regions where different levels of description may obtain. It will be noted that the boundaries between the levels at P_r equals 50 percent are separated by factors of approximately 5 in definition thus satisfying the rule of thumb. The reader will of course recognize the tenuous nature of the arguments that produced these curves and will treat them only as practical working hypothesis or as useful guidelines of a design.

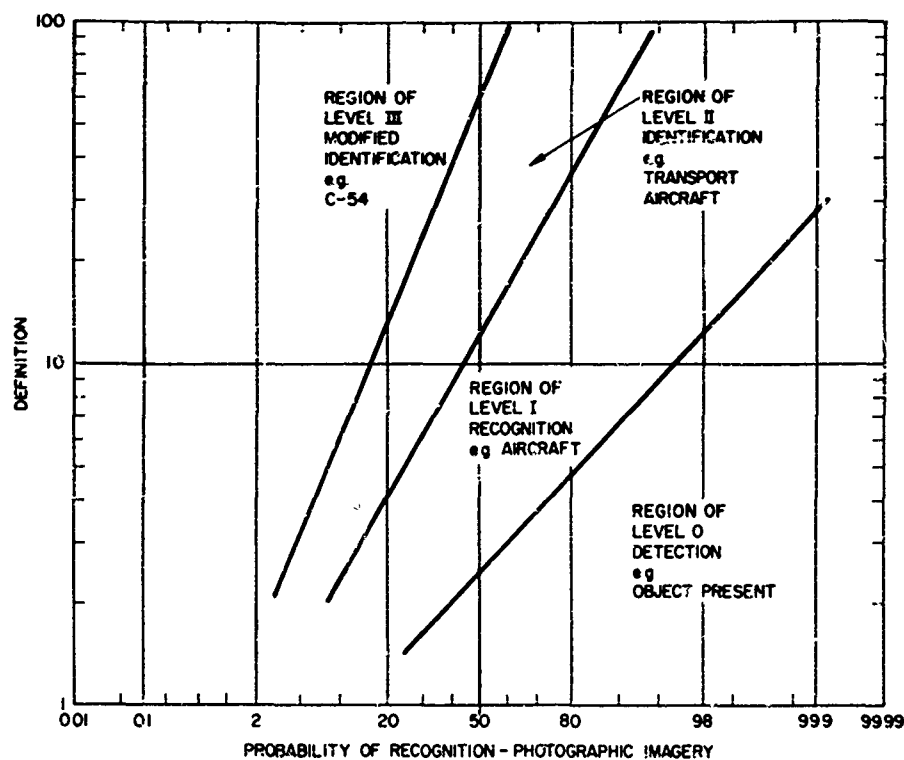


Figure 36. Definition VS Probability of Recognition

These data were derived from studies using photographic imagery. In an airplane the radar case is of more interest, and the validity of generalizing from data using photographic imagery to predict performance using radar imagery is, of course, subject to doubt. We believe however that those doubts can be allayed if the process that the observer uses in each case is considered. In both cases the observer is looking for a pattern formed by visual contrast and in both cases shape is presumed to be the primary cue used for target recognition. One would expect, then, that definition--the number of resolution cells placed on the target--would similarly affect the utility of both the radar and photographic imagery, for in both instances increasing definition has the effect of crispening the shape of visual objects. Because the observer bases his classification on his ability to resolve shape, it seems rational to assume that the form of the functional relationship between definition (resolution) and probability of recognition would be similar for both radar and photographic imagery. For photographs this relationship can be represented by the hypothetical curves shown in Figure 36.

Using the curves in Figure 36 as a paradigm, one would expect that the curves for radar would have similar slopes but be displaced slightly to the left by an unknown amount. That is, with equal resolution, recognition performance using photographic imagery will be slightly superior to that using radar imagery. This bias is likely because film is roughly sensitive to the same energies as the eye with the consequence that a photograph looks familiar and little transformation is required for recognition. This is less true of radar imagery--things that look bright to a radar do not necessarily appear visually bright and some experience is necessary to interpret radar imagery quickly. This, coupled with small geometric differences between the two types of imagery, suggest a slight bias in favor of photographic imagery.

In the study by Bennett et al (1963), conducted at IBM, the investigators were interested in the effects that contrast, "grain," and resolution had on recognition performance. Using photographic imagery processed to yield the required contrast, grain, and resolution, a trained subject was asked to tag the target with crosshairs, categorize it by use of a keyboard, and indicate the level of confidence of the classification. A variety of military targets were used. Two; fighter aircraft and trucks, were similar to those used in the Jennings study which allows a comparison between these two sets of data. The fighter mean size was 50 feet and the truck mean size 20 feet. The use of these dimensions coupled with sensor resolution estimates allows us to calculate the definition. Assuming that the composite score "recognition effectiveness" as used in the Bennett study is approximately the same as P_r , then P_r as a function of definition may be plotted as shown in Figure 37. These data are in good agreement

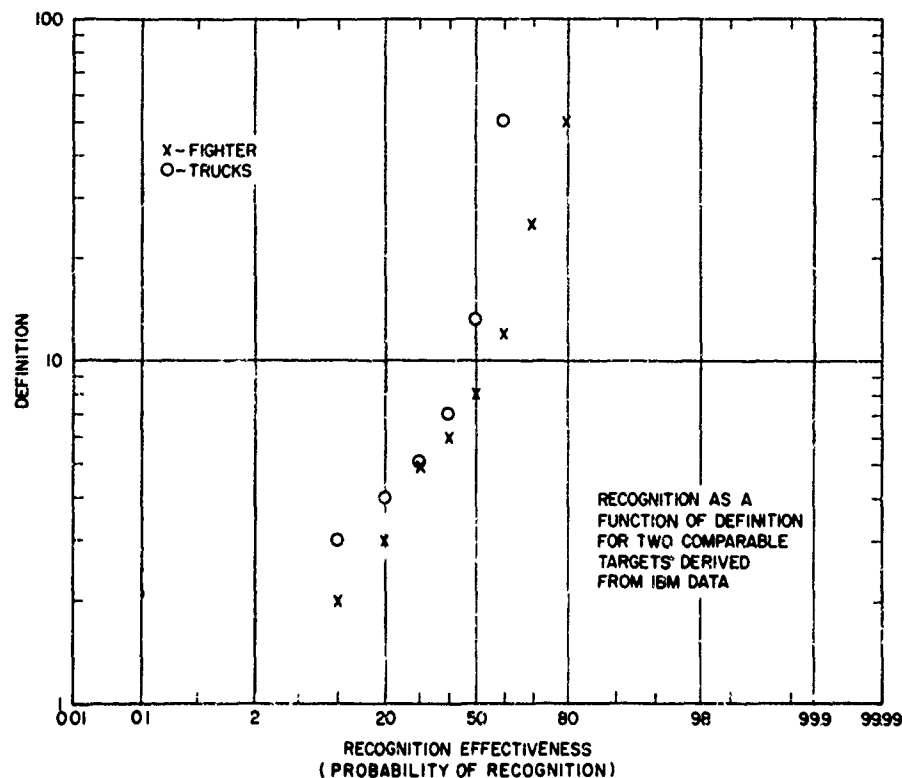


Figure 37. Definition VS Recognition Effectiveness for Two Targets

with the Jennings data although the Bennett curves show that the observer's were somewhat less capable of recognizing a target at a given definition. Considering the differences in technique, imagery, etc., the agreement between these two sets of data can be considered remarkable in this field. Although we have freely used the IBM data, with their kind permission, it should be pointed out that Bennett et al do not share our optimism with respect to the validity of expressing resolution requirements in terms of target size.

The reader should be cautioned that such conclusions as have been drawn above should not be used indiscriminately and should not be used to lull the designer into a sense of security. This formulation was conceived to provide approximate guidelines for physical design and should be construed in that light.

Scale

The best empirical information on scale may be found in the Bennett report cited previously. For each of the three scales they used in their experiments, performance data were plotted against estimated resolution. Figure 38 shows these results with what they call "rationalized curves" fitted. These curves show that a given scale is useful up to the point where, with that scale, the displayed resolution elements become much larger than the acuity limits of the eye. When the eye can resolve to the limit of the rest of the system it does no good to make the image larger by expanding scale. These curves also show that if the display scale is too small, sensor resolution is wasted because the eye cannot resolve to a comparable value. The desirable scale according to the IBM investigators is about 750 times the resolution for displays viewed from about 12-18 inches with the unaided eye. The data quoted from the Bennett study are in good agreement with similar data gathered by Williams, Simon, Haugen, and Roscoe (1960).

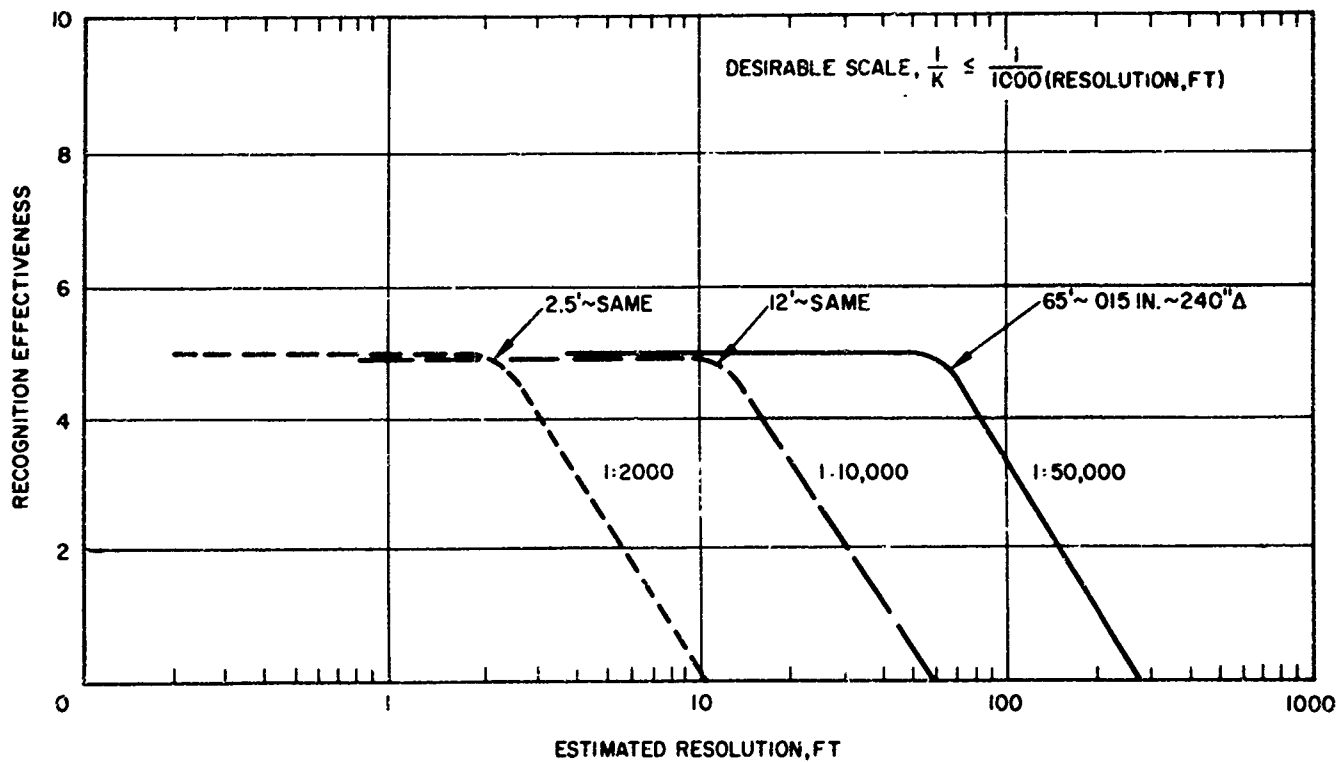


Figure 38. Effectiveness as a Function of Resolution, by Scale

A table from the Williams study is reproduced in Table VIII. If the rule is adopted that the best scale is 750 times the resolution then for the data shown in Table VIII the best scale for 55-foot resolution is 1:41250; for 26-foot resolution, 1:19500; and for 13-foot resolution, 1:9750. It can be seen that this rule accounts very well for the trends observed.

The rule also agrees with what one would rationally calculate if the limit resolution of the eye were assumed to be 3 minutes of visual arc in the operating environments of these experiments. Three minutes at 18 inches viewing distance subtends .016 inches. If we let this equal a

TABLE VIII . TYPES OF TARGETS IDENTIFIED AT VARIOUS
SCALE FACTORS AND RESOLUTIONS

Resolution (Ground)	SCALE FACTOR		
	1:40, 000	1:27, 000	1:12, 000
55 feet	<p>Scale or pattern:</p> <ol style="list-style-type: none"> 1. Terrain features 2. Activity areas 3. Airstrips <p>Relationships, context:</p> <ol style="list-style-type: none"> 1. Functional areas of city 	<p>Same types of targets as at 1:40,000, but with some loss of accuracy.</p>	<p>Same types of targets as at 1:27,000, but with great loss of accuracy, especially in identifying functional areas of a city.</p>
(SCALE ENLARGEMENT IS DETRIMENTAL)			
26 feet	<p>Shape or pattern:</p> <ol style="list-style-type: none"> 1. Marshaling yards 2. Irregularly shaped bldgs (300x250 feet) <p>Relationships, context:</p> <ol style="list-style-type: none"> 1. Aircraft 	<p>Same types of targets as at 1:40,000.</p>	<p>Shape or pattern:</p> <ol style="list-style-type: none"> 1. Outdoor theaters 2. Cemeteries 3. Oil tanks 4. Railroad round house
(SCALE ENLARGEMENT IS ONLY SLIGHTLY BENEFICIAL FROM 1:27,000 TO 1:12,000)			
13 feet	<p>Shape or pattern:</p> <ol style="list-style-type: none"> 1. Aircraft (100 feet) 2. Outdoor theaters 3. Golf courses 4. Storage sheds for produce (150x20 feet) 	<p>Same types of targets as at 1:40,000, but with greater accuracy.</p>	<p>Relationships, context:</p> <ol style="list-style-type: none"> 1. Warehouses 2. Factories (stocked materials) 3. Oil processing plants 4. Gravel pits (machinery) 5. Institutions
(SCALE ENLARGEMENT IS BENEFICIAL)			

resolution element and assume, for example, a system with a resolution of one foot. then the field of view of a 12 inch display will be 12 divided by .016 or 750, i. e. , a scale of 1:750.

In summary there is one best scale for target location when the target must be recognized by its shape signature. Enlarging the scale and the image beyond the critical point adds no information that can be utilized by the operator. Reducing the scale means that information gathered by the sensors is lost because it cannot be resolved by the eye. If the display size is limited to 10-12 inches, a sensor capacity of 700 to 1000 resolvable elements along one axis is about the limit that the observer can use with unaided vision.

Another consideration which may affect the choice of scale is the required field of view. If a display is used for navigation updating, the required field of view will be determined, in part, by the total position errors accumulated between updating periods. The field of view should be something more than twice the size of the likely error--the requirement is that a checkpoint be included in the field of view at some level of certainty. Such considerations, when coupled with limitations on display size, may dictate a scale other than the optimum.

If optimum scale is the sole criterion, the desirable size of the display for these applications can be calculated when the system resolution, operator viewing distance and capacity of the sensor are known. The results of such calculations using a more optimistic value for limit eye resolution are shown in Figure 39. If, because of space limitations the display must be kept within a certain small size, then the designer should be aware that this may seriously compromise the expected performance of the system.

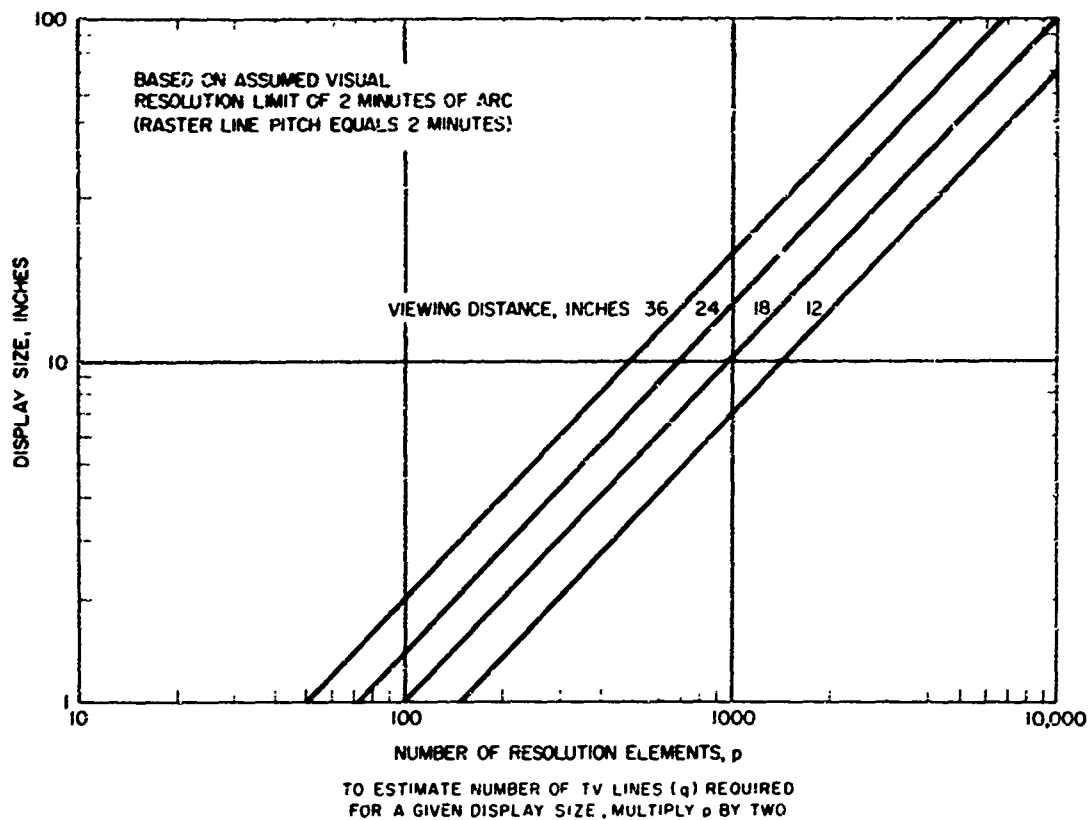


Figure 39. Required Display Size (See PP-ff for Conversion to TV, q , Resolution)

Briefing and Reference Materials

The importance of a priori information was discussed briefly in previous paragraphs. That the form of the reference material is critical is shown by the great effort that SAC has put into generating radar prediction charts. In general, it has been found that even the slightest briefing will improve the operator's ability to recognize landmarks or checkpoints. There is, however, a remarkable scarcity of data in the open literature on precisely what the relationship should be between the reference material and the real time display. This is a critical problem even for unaided vision when the display is the natural full-colored three-dimension world, for McGrath, Osterhoff and Borden (1964), have shown that the coding of map contents has a marked effect on the ability of a pilot to identify visual checkpoints during low level flight. It should also be mentioned that a priori

briefing acts as a suggestion and may form in the observer a "set" or expectancy to see a certain kind of target with the consequence that the false alarm rate may increase.

A study was conducted at Hughes Aircraft Company, Culver City, in connection with the CONDOR Program in which the real time display was a TV monitor and the operator's task was to identify a specific target on which he had been briefed. Vertical photographs at several scales and geodetic survey maps at a scale of 1:24,000 were used as briefing materials. The results can be summarized by noting that the closer the briefing material resembled the real time image at the time the subject first saw it, the better was the performance. Photographs at any scale tested were better than maps, photographs at a scale corresponding to the initial real time image scale were better than those that differed.

In an earlier study at Hughes, conducted as part of the Advanced Tactical Strike System contract, it was found that adequate briefing was of overriding importance. Unfortunately not too many rigorously supported conclusions can be drawn about the specific nature of desirable briefing materials, but in one case such an inference is possible. The subject was required to designate a specific target as quickly as possible on radar imagery derived from an APQ-55 system. Some were briefed using maps and charts and others using high resolution aerial photography. The results are as follows:

	MAPS AND CHARTS	AERIAL PHOTOGRAPHS
AVERAGE TIME TO DESIGNATE	36 sec	17 sec
FALSE ALARMS	22%	0

In spite of the fact that the utility of appropriate reference materials is universally recognized, little is known about the precise nature that such reference material should take. Very little systematic work has been done

on this problem and the design of such materials represents one of the most pressing problems to be solved before the raw sensor displays may be fully exploited. Because it is not an autonomous sensing and data processing issue the requirements for such materials will not be discussed in later sections of this report. It should not be inferred, however, that this omission implies unimportance but only that it should be handled under a rubric other than sensing and data processing requirements.

PICTURE QUALITY REQUIREMENTS

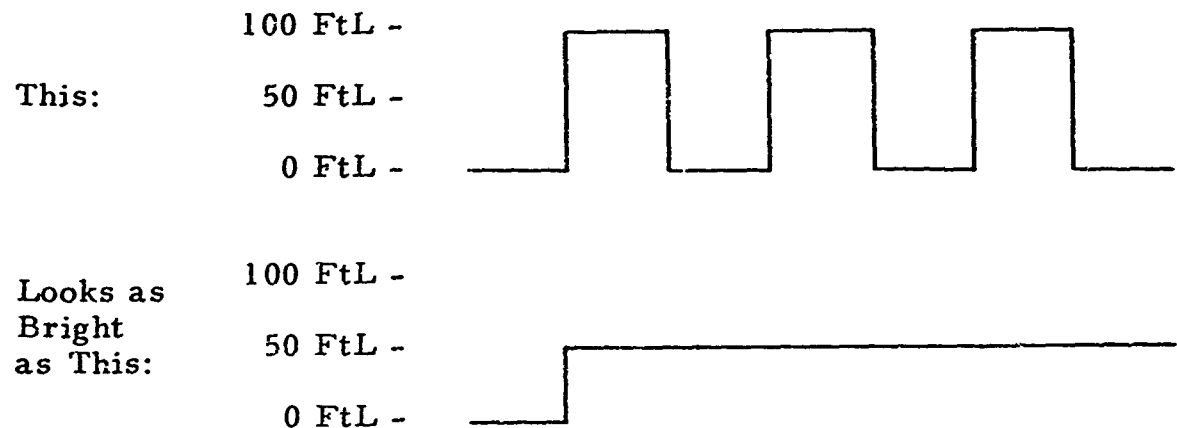
The utility of pictorial raster scan displays depends not only on the information contained in the display and the method of encoding it but on the quality of the displayed image. One might have conceived the best of all possible symbols and images to no end because the display medium is inadequate and nothing can be seen, or what can be is of poor quality. This is not a minor problem for the visibility of raster scan displays in daylight is notoriously poor. It is worth spending some time stating the general requirements that will enable the picture to be seen without undue visual fatigue. The critical problem is to get a flicker free display bright enough, contrasty enough, and sharp enough to see in bright daylight. For this reason very little time will be spent on viewing requirements at low light levels for a dim display can be achieved with a variable filter. The major variables of interest are field rate, frame rate, data rate, highlight brightness, contrast, dynamic range, and resolution. The use of filters and coatings is also of interest.

The effects on visibility and image quality of color, adaptation time, target shape, viewing time, drugs, and operator idiosyncrasies will not be considered.

BRIGHTNESS AND GREY SCALE

It is convenient to specify the brightness required in terms of the integrated brightness even though the raster scan is physically intermittent. At a 60 cps frame rate the apparent brightness will be that of the equivalent

amount of luminous energy spread over a reasonable integrating interval—say one or two seconds. The peak brightness required to reach the needed integrated brightness level will depend primarily on system duty cycle and phosphor decay characteristics.



Data is available to assist in establishing the display brightness and contrast requirements. These laboratory data enable us to estimate;

- 1) the values required to reach a 50% threshold of visibility
- 2) the values required to reach a greater than 50% threshold
- 3) the values required to reach an operationally useful image
- 4) the values required to compensate for an adaptation mismatch
- 5) the values required for achieving clearly discriminable grey shades.

By judicious use of these sets of data, estimates of required brightness and contrast may be reached. The use of these data will be illustrated in the following examples.

The basic data to provide the starting point for all estimations may be generated from Blackwell's study (Blackwell, 1946) of the contrast thresholds of the human eye. The curves in Figure 40 are plotted from data gathered in that study, and they show the 50% threshold as a function of background brightness, contrast, and target size. The 50% threshold is the level at

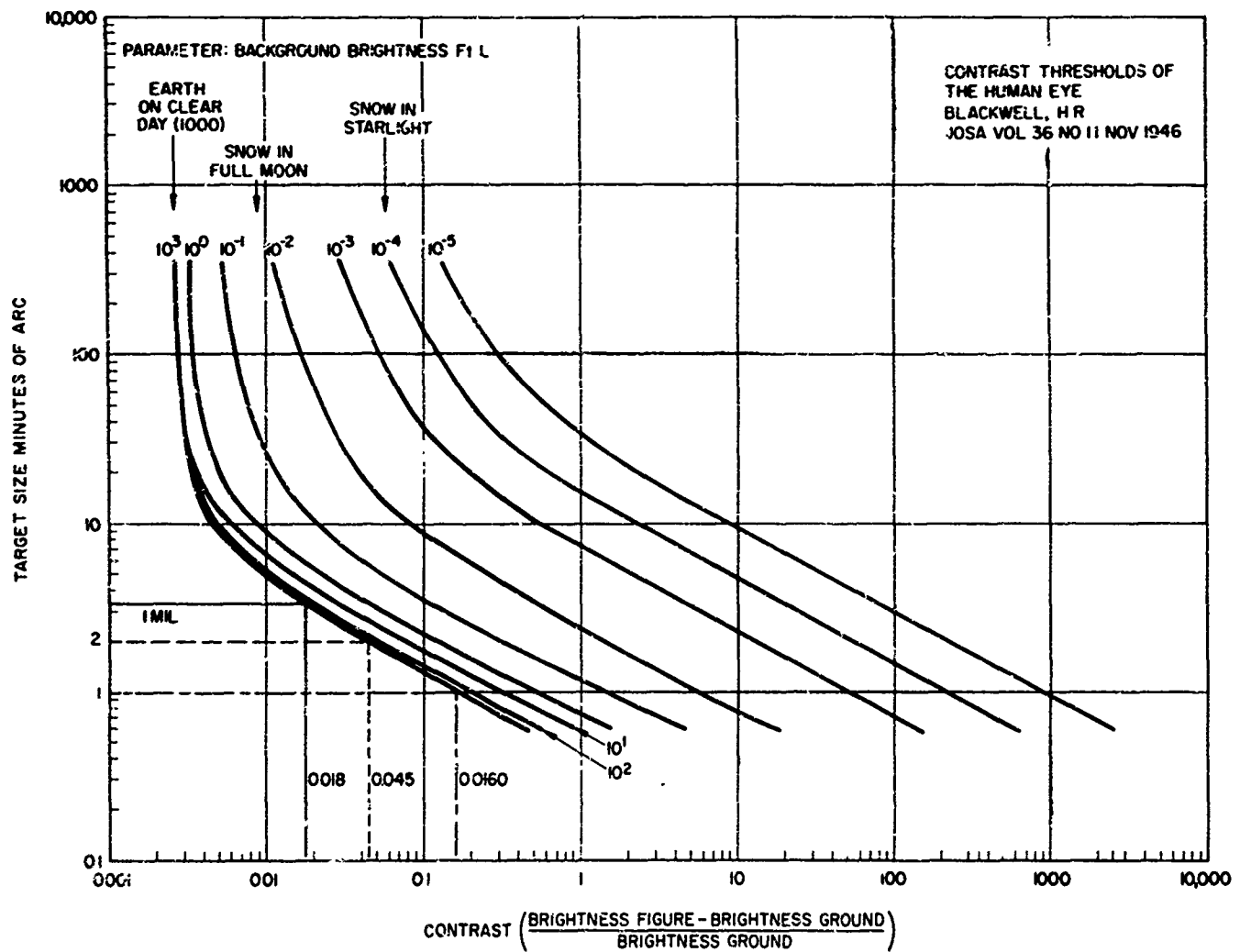


Figure 40. Contrast Thresholds of the Eye (Adapted From Blackwell)

which the target was detected 50% of the time. Figure 41 (adapted from Blackwell) is a conversion curve that may be used to estimate thresholds other than the 50%.

The background brightness in a skeletal display is the brightness of the tube face where there is no image. The level of this background brightness may be markedly different from the surround brightness — for example, the sky. As long as the ratio of the surround brightness to the background brightness stays below 10, there is no marked effect on the contrast threshold. If the surround is brighter than the background by more than a ratio of 10, then the surround will start to affect the contrast required in varying degree due to an adaptation mismatch. Figure 42 shows these effects. The solid curve is based on data from a study conducted at General Electric Co., Ithaca, (Purdy, 1959) and shows the correction factor to use when the surround (the sky) is markedly brighter than the background.

Figure 43 adapted from Chapanis (1949) shows how acuity is affected by contrast and background brightness. In the skeletal display the requirement is not only that a thin line element be visible but that readout accuracy be maintained by requiring that the separation between two elements be visually resolved when the separation is equal to a line width. For this reason the curves in Figure 40 and the curves in Figure 43 should in each such case be compared, and in calculating the brightness requirements the most demanding value should be used.

Image motion will not effect thresholds unless the velocity of images at the eye exceeds 30° per second. This will normally occur only on the TV and contact analog VSD displays when the aircraft flies at high speed at low altitude. The V/h ratios that will produce blur is shown in Figure 44 as a function of depression angle.

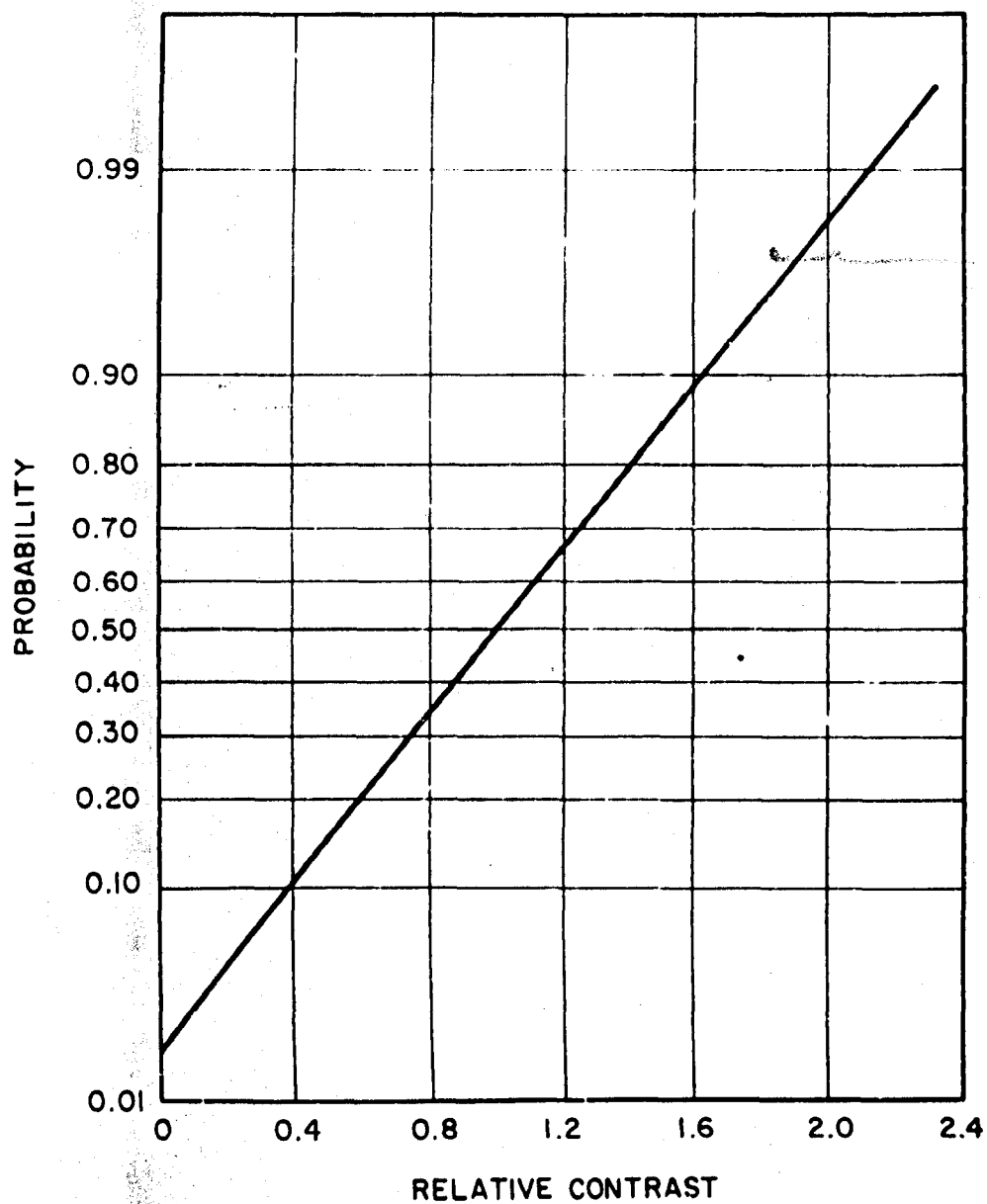


Figure 41. Curve to Convert 50% Threshold to Other Probabilities

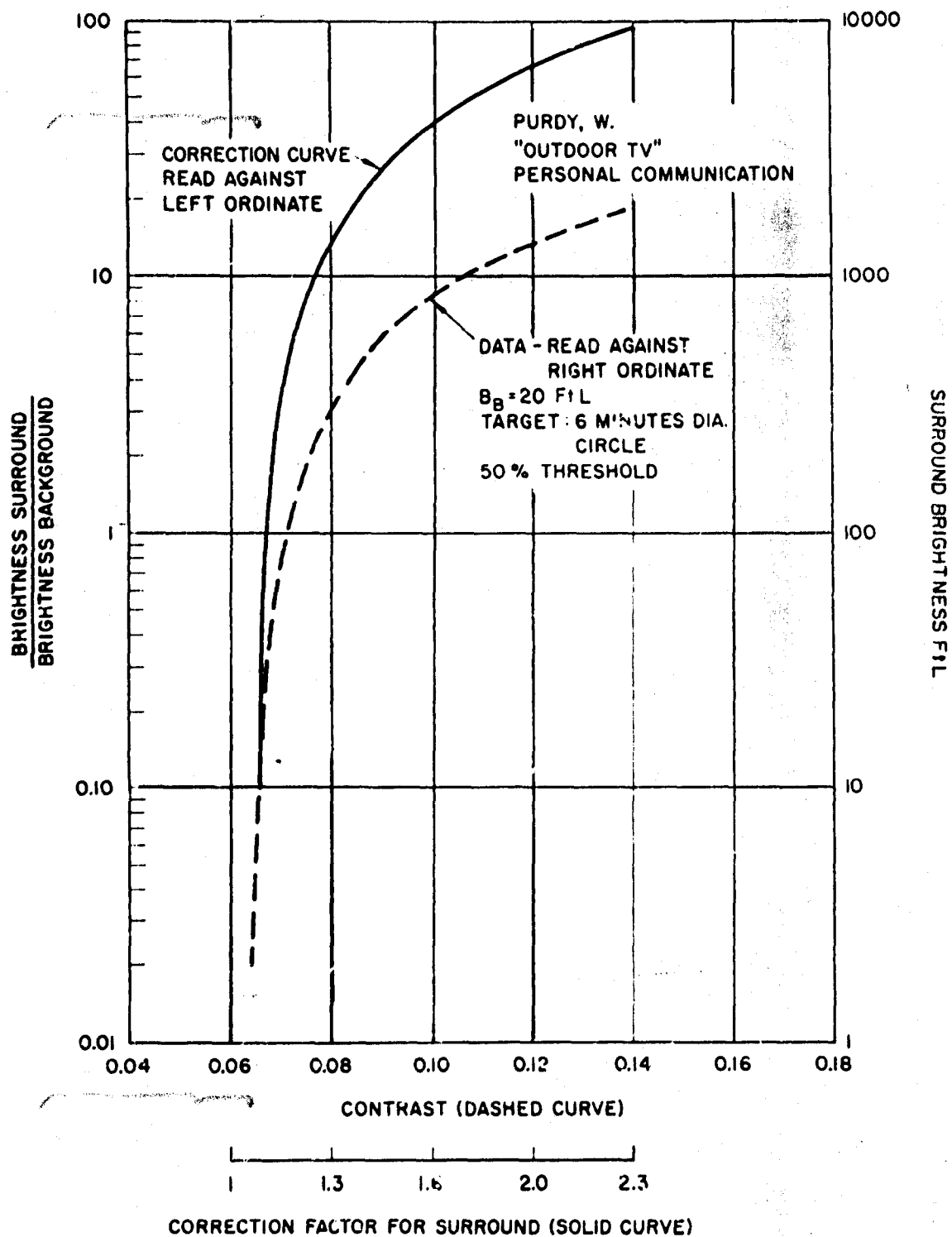


Figure 42. Effects of Surround on Contrast Threshold

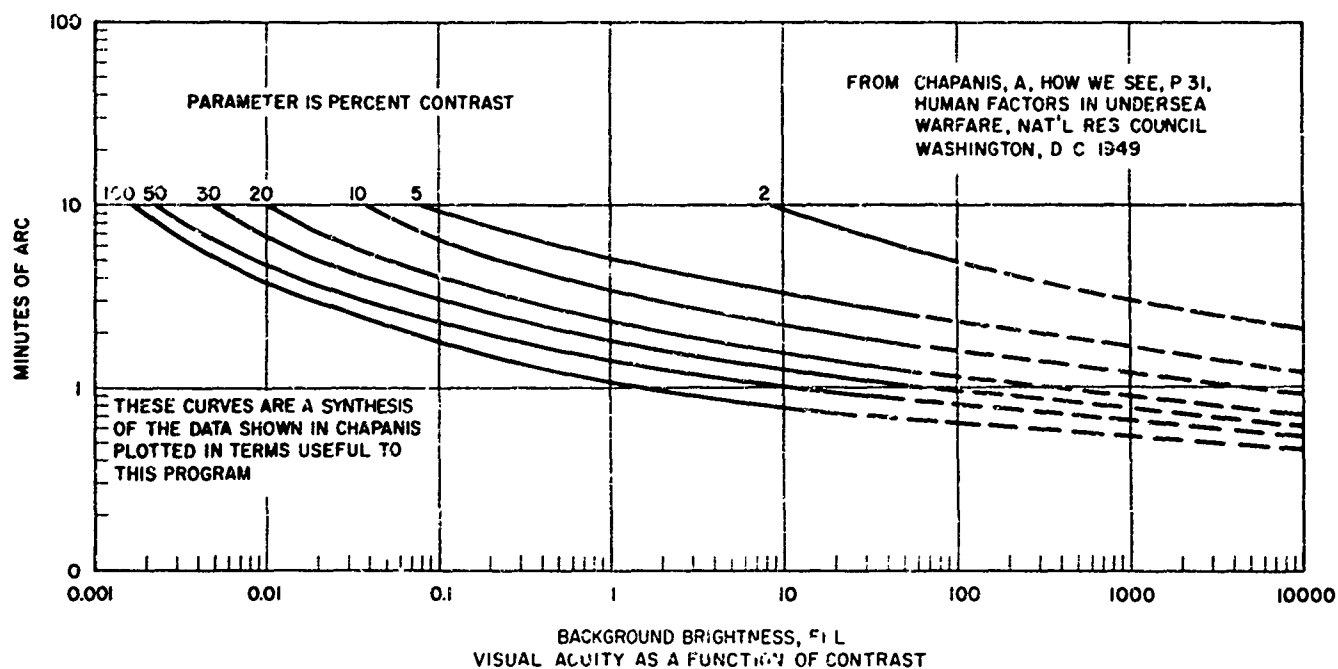


Figure 43. Visual Acuity as a Function of Contrast

The information contained in these figures may be used to estimate the minimum required brightness and contrast of the skeletal displays. The best way to show how this information may be used is by using a series of representative examples. Suppose the following:

We wish to paint the symbols shown in the skeletal panel mounted landing display illustrated in Figure 19 with lines one mil in width. (One mil is about 3.4 minutes of arc.) The display is hooded and panel mounted so that the tube

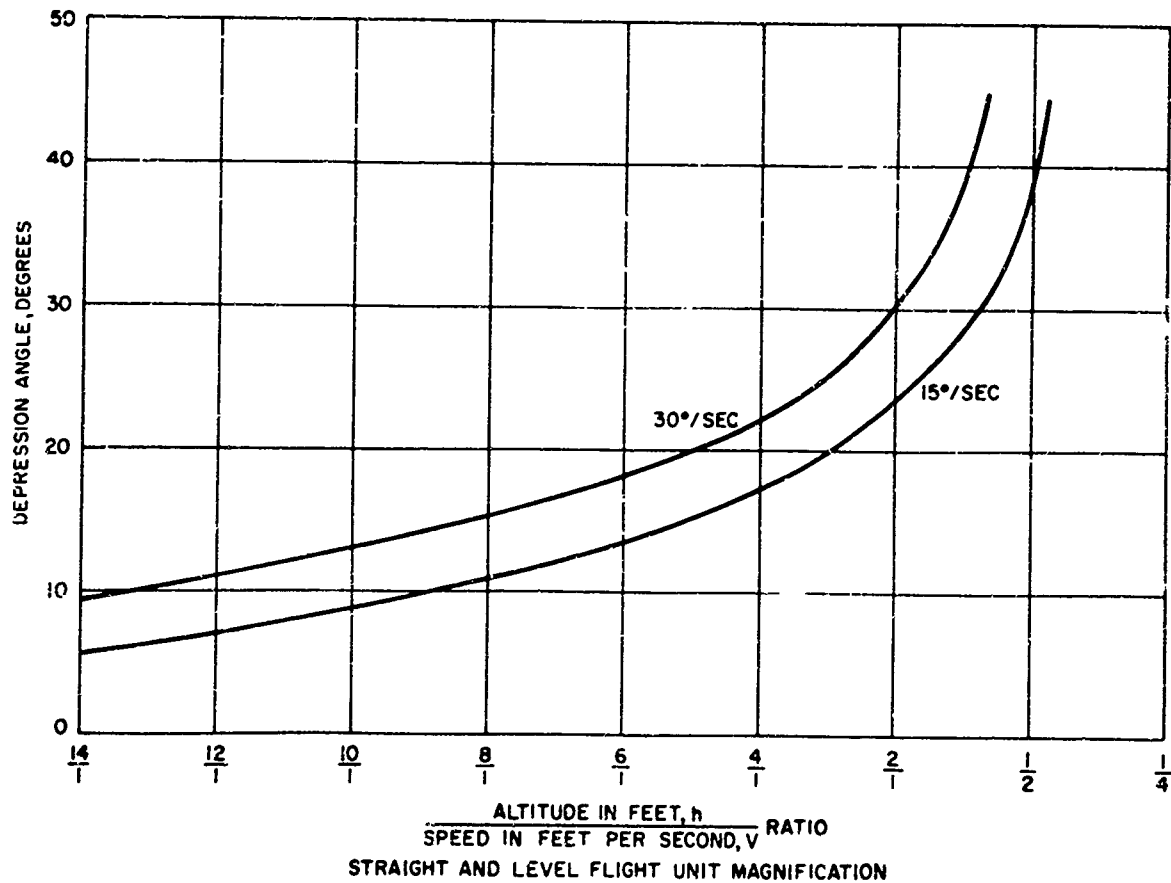


Figure 44. Blur Threshold as a Function of V/h Ratio and Depression Angle

background brightness is assumed to be 20 FtL and the surround brightness (the sky) is about 2,000 FtL. From Figure 40 we find that the required contrast for the 50% threshold is about .03. Although our image is only one mil wide it is in essence a long line, and from corollary data it is known that such lines are somewhat easier to detect than simple patches.

However, the line was made one mil wide in order to retain precise readout accuracy, and we should therefore like to be able to resolve two lines separated by one mil. Figure 43 shows that the contrast required for that order of acuity is closer to .05. This more stringent value will therefore be used.

To raise the probability of detection to .9999, Figure 41 is consulted, and it is found that .05 must be multiplied by a factor of 3 which yields .15. Even at this level of contrast the image is ghostly. Muller (1956) has shown that this latter value (.15) must be again multiplied by a factor of at least five (Muller's constant) before the image is bright enough to be viewed comfortably. When multiplied by five the required contrast is .75.

However, because of the large brightness difference between surround and background, the curves illustrated in Figure 42 must be consulted. It is found that we must multiply by about 1.2 to correct for the adaptation mismatch. The required contrast is now .9. Using the equation

$$\frac{B_f - B_g}{B_g} = .9,$$

it is found that the minimum integrated brightness for the lines under these conditions is approximately 38 FtL.

At this point it will be useful to utilize a constant, K, that will consist of the value necessary to raise a 50% threshold to 99% (a factor of three) and "Muller's constant," (a factor of five) to raise the image from a ghost to a more substantial picture. The value of this constant, K, to be used in subsequent analysis will be 15.

The same procedure can be used to estimate the brightness required for an unhooded display where the tube background brightness will be caused chiefly by light reflected from the sky as will be the case in daylight conditions. With no filters and conventional TV phosphors the tube face will reflect about 70% of the incident light. Representative ambient light levels during daytime are as follows.

overcast day: 100 Ft Cdl's

clear day (not direct sunlight): 1000-2000 Ft Cdl's

direct sunlight: 10,000 Ft Cdl's

Assume a clear day not in direct sunlight. Using the lower value of ambient the tube background brightness then will be about 700 FtL. From Figure 40 the contrast required for a one mil line is about .02. This value multiplied by K of 15 yields .30. The increment of brightness required then is about 210 FtL.

Consider next a head-up display (HUD) requiring only line images with a line width of one mil and a background brightness of 2000 FtL (the sky). The contrast threshold is .018. Multiplying by K yields a contrast of .27. With a neutral combining glass, the total light loss through the optical train to the eye may be 80%. Therefore the brightness of the line pattern on the tube face needs to be on the order of 2700 FtL.

The same one-mil pattern on a HUD against a background brightness of 10,000 FtL will require a brightness of about 13,500 FtL.

It should be emphasized that all of the above values are minimal values where the image will appear somewhat "ghostly".

Let us now consider a more complex display like a contact analog that uses patches of black and white to paint the necessary surfaces. In an achromatic contact analog, brightness will be used to code elements in the display so such elements will need to be visually discriminable in brightness. For example, the flight path should be brighter than the ground, and other symbols may be brighter than the flight path. Several brightness levels are required rather than the two values used in the examples cited previously.

The needed grey scale may be calculated in the same way as the other examples although at the slight additional hazard of an extrapolation. Assume again for the hooded case a background brightness of 20 FtL, a surround brightness of 2,000 FtL, and that the smallest patch we want to see subtends one mil on a side. From the previous example, the patch brightness was estimated to be 38 FtL. The ground plane, then, would be formed of patches of 20 FtL and 38 FtL. Once again it should be remembered that such contrasts as these, whilst clearly visible, are not what could be called good quality. However, let us use 20 and 38 for the ground. If the sky is not patterned it may be 20 FtL. If patterned, 20 and 38 FtL may be used if pattern rather than brightness can be used to discriminate ground from sky.

Elements comprising the flight path should be still brighter. They must be seen against a background of at least 40 FtL. The required contrast for one-mil patches is still about 0.9 so the path brightness needs to be about 76 FtL.

Still other symbols need to be seen against the brightest parts of the flight path. Calculating as before it is found that these should be minimally 111 FtL.

The contrast requirements calculated from these data are in good agreement with some observations we have made in our own laboratories where we have been informally investigating the contrast requirements for useful shades of grey in cathode ray tubes. In general, it has been found that a 2:1 contrast ratio is needed for pleasing and easily discriminable grey shades when the display is viewed under medium to high ambient (50-3,000 FtL). This corresponds to

$$\frac{B_f - B_g}{B_g} = 1.$$

If, therefore, one wants five shades of grey, a dynamic range of 16:1 is required; if eight shades, a range of 128:1, etc.

If we assume that the background brightness is 0.7 of the ambient because of the tube reflectance, then a table can be constructed to show the brightness required for a given ambient and the desired number of grey shades for an unhooded display with no filters. See Table IX.

Table IX. BRIGHTNESS REQUIREMENTS FOR DISPLAY

Dynamic Range		2:1	4:1	8:1	16:1	32:1	64:1	128:1
Shades of Grey		2	3	4	5	6	7	8
Brightness Range Required, FtL - Reflectance Plus Signal (Unhooded, 70% Reflectance, No Filter)								
Ambient	1 FtL	.7-1.4	.7-2.8	.7-5.6	.7-11.2	.7-22.4	.7-44.8	.7-89.6
	10 FtL	7-14	7-28	7-56	7-112	7-224	7-448	7-896
	100 FtL	70-140	70-280	70-560	70-1120	70-2240	70-4480	70-8960
	1000 FtL	700-1400	700-2800	700-5600	700-11200	700-22400	700-44800	700-89600
	10,000 FtL	7000-14,000	7000-28,000	7000-56,000	7000-112,000	7000-224,000	7000-448,000	7000-896,000
70% Reflectance, 10% Filter Tube Brightness Required, FtL								
Ambient	10	0.7-2	0.7-4	0.7-8	0.7-16	0.7-32	0.7-64	0.7-128
	100	7-20	7-40	7-80	7-160	7-320	7-640	7-1280
	1000	70-200	70-400	70-800	70-1600	70-3200	70-6400	70-12800
	10,000	700-2000	700-4000	700-8000	700-16000	700-32000	700-64000	700-128000

It can be seen that to get a display with five clearly distinguishable shades of grey that will be useful, in an ambient of 1,000 FtL requires a tube with a highlight brightness of 11,200 FtL which would indeed require a very bright tube. The values in this table deal only with requirements and should be used only to indicate the approximate, and somewhat stringent values required to meet the criteria suggested in this discussion. As will be shown later, such display devices seem not out of the question. Assume, however, a display with a filter that transmits 10%. In a 1,000 FtL ambient the background brightness will now be seven FtL for only 10% of the incident light is transmitted both before and after it is reflected from the tube face.

Five shades of grey can now be achieved with a highlight brightness on the tube face of approximately 1,600 FtL (160 to the eye, 1,600 on the tube).

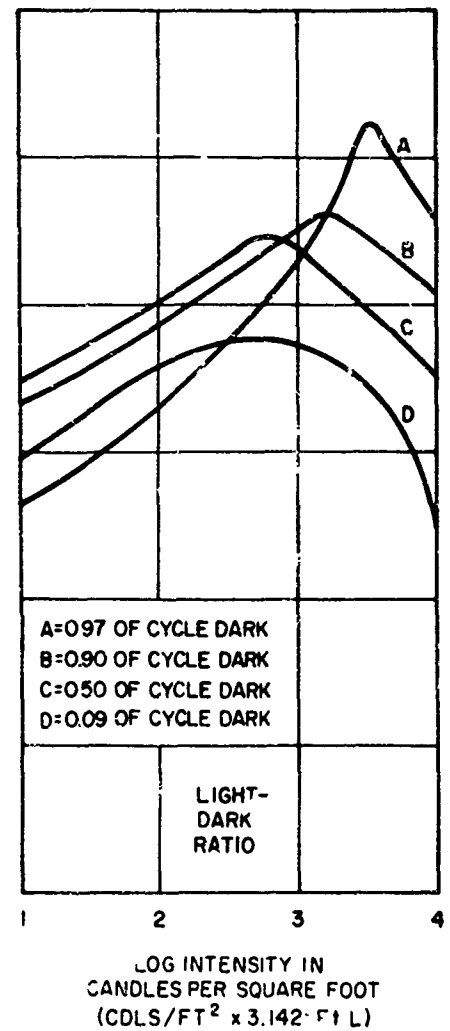
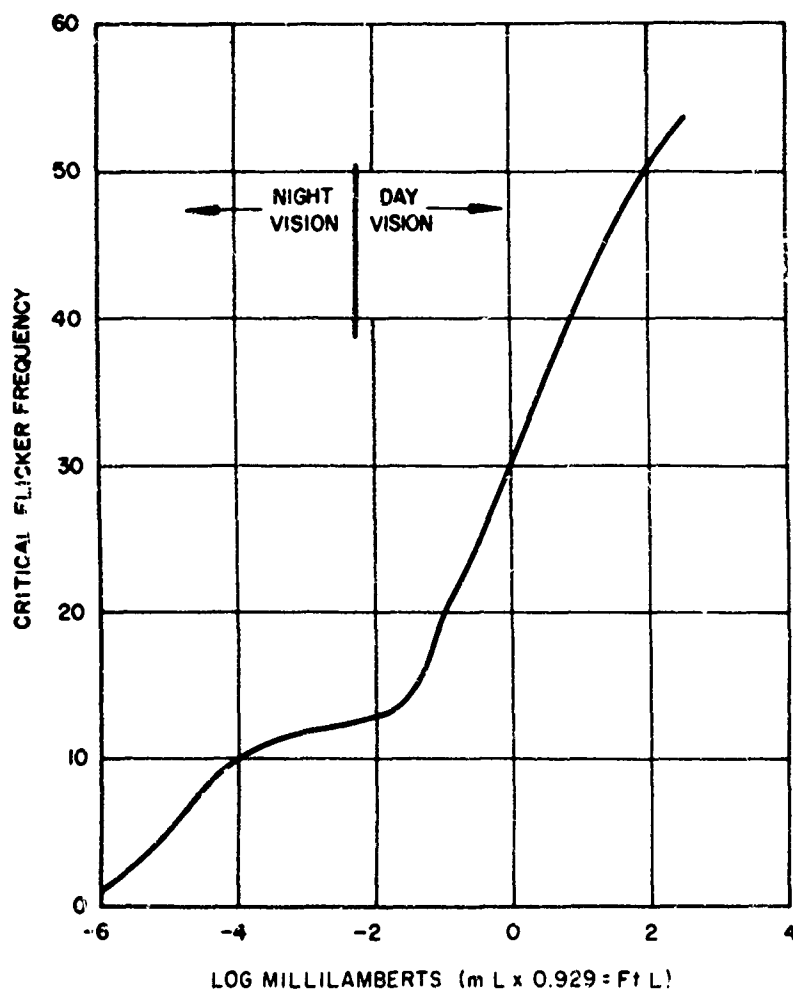
It has also been found, however, that even a 2:1 contrast is insufficient if the brightness of the adjacent grey steps is markedly different from the ambient. Due to an adaptation mismatch the dimmer greys will wash out. The conditions under which this occur are difficult to estimate from existing data, but a reasonable value would be when the low end of the display brightness approaches 1 - 10% of the ambient. A 10% criterion will yield a higher quality display than a 1%. This means that the brightness at the eye of the dimmest shade of grey should never be less than 1 - 10% of the ambient. For example, if the display is to be viewed in a 1,000 FtL ambient, and a high quality five shades of grey image is required, then at the eye the dimmest grey should be 100 FtL and the brightest 1,600 FtL. If a lower quality display can be countenanced the dimmest grey could be 10 FtL and the brightest 160 FtL.

In short, this discussion says that given an ambient and the requirement for a given number of grey shades, the dynamic range and brightness requirements may reasonably be estimated.

FIELD RATE

The required field rate is derived solely from the characteristics of the eye. A flicker free image is required. Figure 45 shows a characteristic curve of critical flicker frequency, CFF, for a range of illumination brightnesses. These data were gathered in the laboratory where the typical experimental conditions were whole field square wave brightness fluctuations. However, the raster scan picture is not of this type but is created by a beam that results in an extremely high brightness scanning spot that decays according to the characteristics of the phosphor. The conditions under which such a display will flicker are best determined by direct observation of kinescope displays.

Schade (1948) has carried out such observations and the results are shown in Figures 46 and 47. Figure 46 shows that the flicker threshold depends on the viewing ratio, p , (the ratio of the viewing distance to screen



(a) Field Brightness (Duty Cycle Unknown) (b) Illumination Source

Figure 45. Critical Flicker Frequency

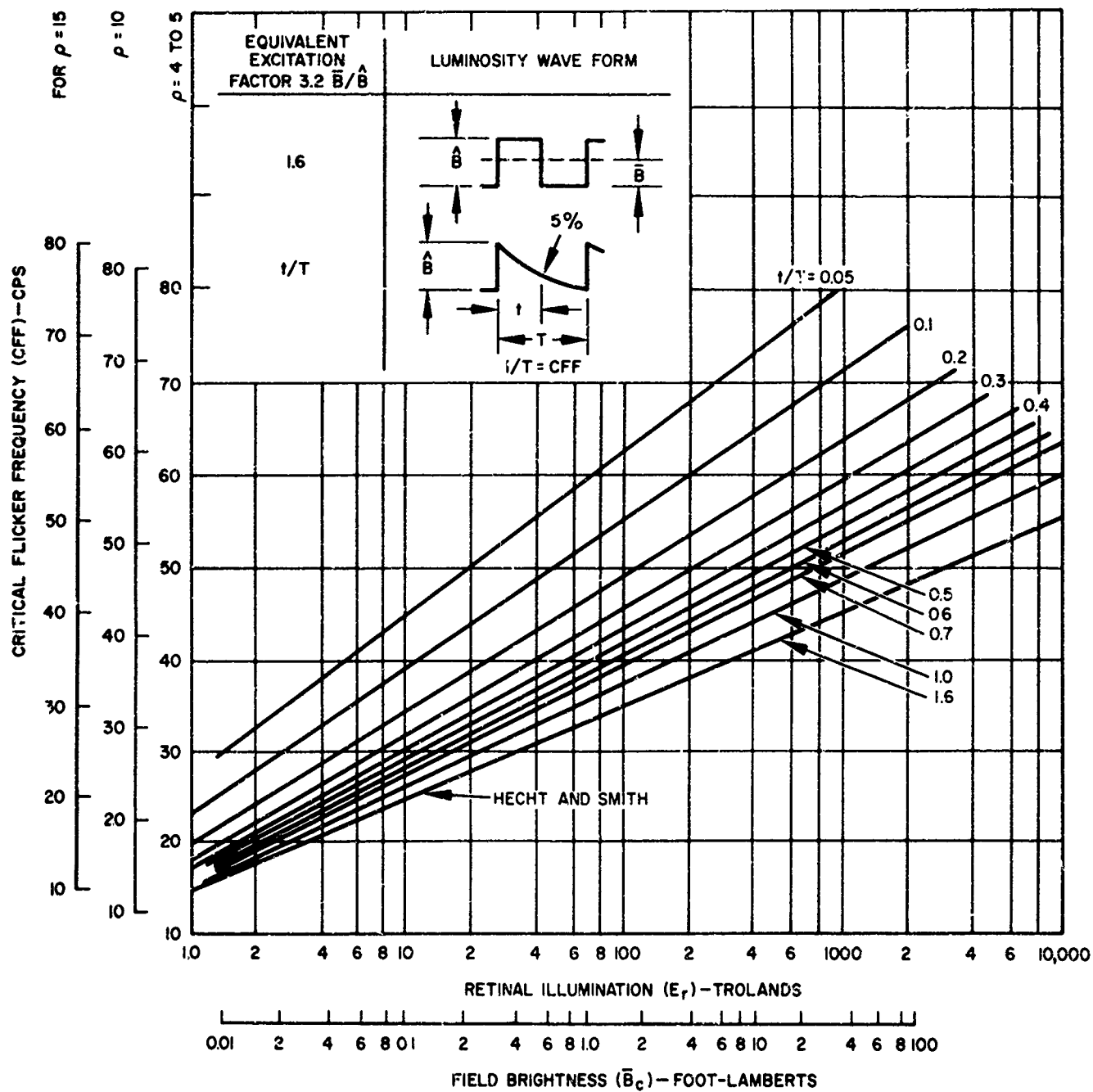


Figure 46. Threshold Flicker Values for Intermittent Illumination
(after Schade)

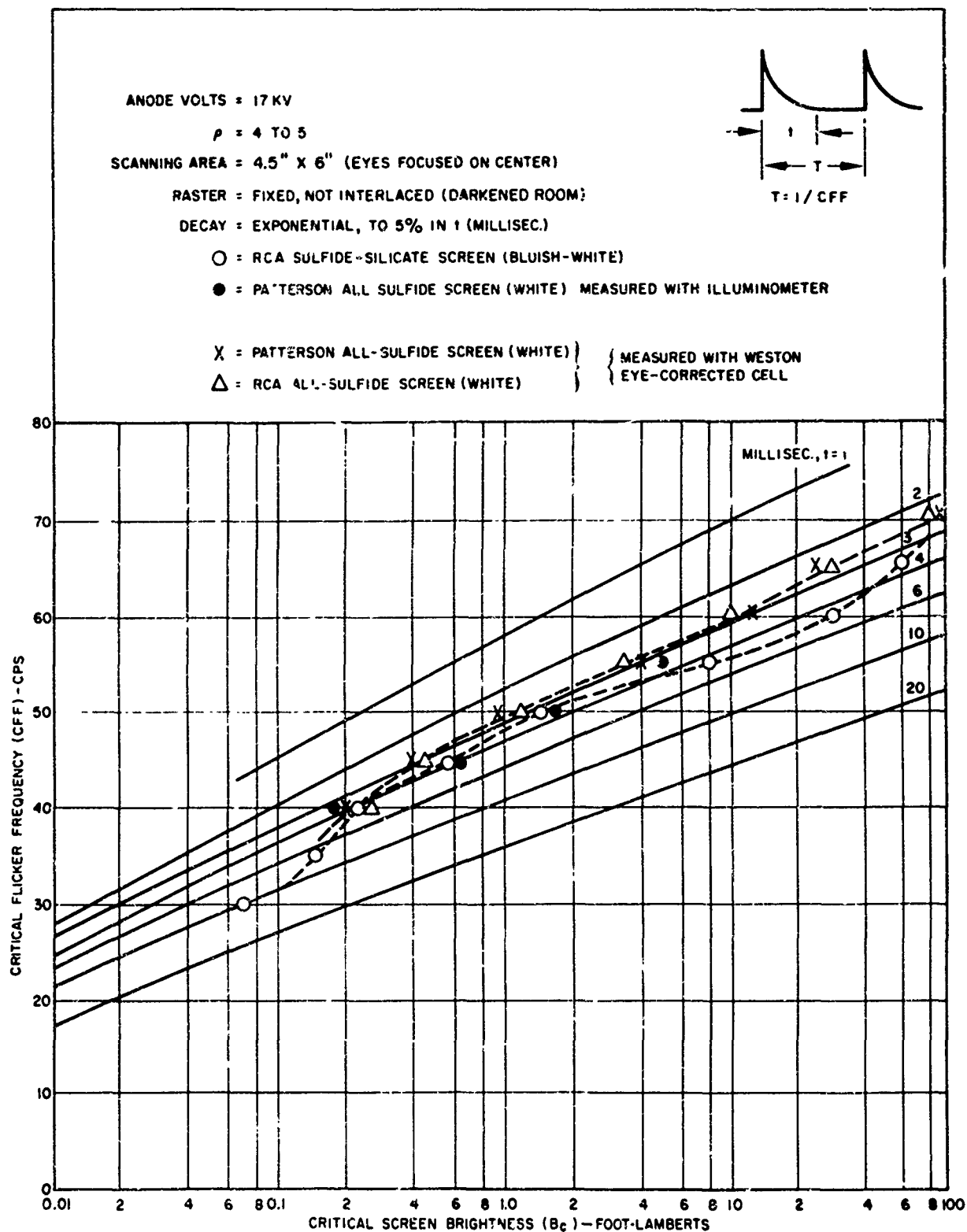


Figure 47. Critical Screen Brightness of Kinescope Fields (White Light) as a Function of Field Frequency (after Schade)

diameter) the field rate, and the phosphor decay characteristics. The viewing ratio affects the CFF because peripheral vision is more sensitive to flicker than is foveal. Figure 47 illustrates much the same information with the addition of some empirical data specific to four different phosphors. All these data were gathered for unmodulated light.

Schade has this to say about the normal picture with modulated light: "It has been observed on normal television pictures that the average brightness level of the image can be raised to a value equaling, roughly, that of the critical flicker brightness, B_c , for unmodulated light without obtaining objectionable flicker of the image. The average screen brightness $\bar{B} = B_c = 10$ to 30 FtL for present phosphors and for a field frequency of 60 cycles per second can, therefore, be considered as a satisfactory value which permits a high-light brightness (\hat{B}) in the order of 50 to 150 foot-lamberts in normal television images."

Presumably to establish the field rate requirements on the basis of average brightness, \bar{B} , rather than peak brightness, \hat{B} , holds only if the peak brightness is used only for highlights and the total area of such highlight brightnesses does not occupy a large portion of the viewing screen.

Although the curves from Schade imply that the CFF keeps increasing with increase in brightness, other data normally show the CFF dropping off or reaching an asymptote in the vicinity of 60 cps. This issue remains unresolved, but it is of more than passing interest because the displays of interest require high brightness levels. If, for example, the average display brightness at the eye were 100 FtL, and $p = 4$ to 5, then according to Schade the CFF would vary between 48 to 85 depending on phosphor decay time. With a fast decay phosphor, $t = 0.05$ msec, the CFF is 85 cps which establishes higher than usual field rate requirements.

DATA RATE

Data rate as used in this context will mean the updating rate of a variable. Data rate will affect the utility of the display in two ways: it will affect continuous control performance on the one hand and influence the appearance of the display on the other.

Variables Important for Performance

The primary determinant of required data rate is the natural frequency of the displayed variable. In general the update rate should be at least double the natural frequency of the displayed variable or double the response rate of the pilot — whichever is lower. If the response rate of the pilot is taken to be four cps, then the update rate for rapidly changing variables should be about eight cps. For slowly changing variables the speed with which events are changing would be the controlling factor.

The larger the anticipation interval — the further ahead in time that the pilot can see — the slower may be the update rate. The exact nature of the relationship is unknown. It seems intuitively obvious that a low data rate with a larger anticipation interval will yield performance that is highly smoothed.

Variables displayed linearly as opposed to nonlinearly permit slower data rates. This is because, paradoxically, they provide less information, prediction is easier, and the required data rate may be slower.

For the vertical situation displays the estimated performance update minimums are:

- 1) All display elements respond to aircraft rotation at 6-8 cps.
- 2) The update requirements for display elements that provide translation information are uncertain at this time, but they will probably vary from 1/2 to 8 cps depending on the considerations discussed above. The data rate requirements for the HSD are so slow that it is not a problem. The one exception is when the HSD may be used as a flight instrument in the helicopter final approach; then the same arguments that hold for the VSD apply to the HSD.

Variables Important for Appearance

The primary consideration is to prevent jumpiness in the display. This is a visual problem and has nothing to do with the control bandwidth of the pilot. Although no hard evidence exists, observations and experience dictate the following:

- 1) All display elements respond to aircraft rotation at 60 cps.
- 2) The update requirements for display elements that provide translation information are uncertain at this time but from observation are presumed to vary from 1-30 cps. The region from 5-15 cps may prove particularly annoying however.

If a vertical situation display is to be used all the way to touchdown, the recommended data rate for response of all display elements to translation is 30 cps.

For other cases the updating rate will depend on the visual range — particularly the updating rate for real world referents like the runway. The obtained visual range will depend on the display-computer resolution if the runway is painted in perspective in its true size. For these cases the further ahead the pilot can see the slower the data rate required. If he has very little anticipatory information, 30 cps is completely safe, eight cps will show only a few percent performance degradation, two to three cps perhaps ten percent degradation, and rates slower than that cannot be recommended unless anticipation is provided.

MEASURES OF RESOLUTION

Until now we have used the term resolution as though there were a universal understanding of its precise meaning. Such is not the case, and it is worth spending some time illustrating the relationships between some common measures of resolution.

Classically resolution meant the ability of astronomers to resolve the separation between adjacent stars. This is still the most common meaning albeit changed slightly to mean the ability of a system to discriminate alternate black and white stripes or some other closely placed high contrast test pattern.

Unfortunately a number of definitions of sensor resolution are in common use. They are generally tailored to specific sensors, their applications, measuring techniques, or simply mathematical expedients. Some definitions are vague or not explicitly stated; others are very restrictive. In most cases it is difficult to deduce significance of sensor resolution on system performance and to make comparisons across sensors. It is hoped that the following discussion will shed some light on this problem.

The generalized concept of image formation is fundamental to understanding of various measures of resolution and their relationships to one another. Image formation is conceptualized as the process of reproducing the signal intensity pattern of object space, to scale, in the image plane. Ideally the intensity at each image point is proportional to that of the corresponding object point, and there is no interaction among adjacent image elements. No known sensor is capable of producing such an ideal image. In reality the signal corresponding to each object point experiences a spread through the sensor so that its image is not a point but a blur which is most intense at the geometrical image point and extends over the entire image plane. The normalized intensity distribution of the point image blur is defined as the point spread function or the impulse response of the sensor. The shape of the point spread function depends on the physical parameters of the sensor. Typical profiles are shown in Figure 48. To a first approximation the point spread function of a sensor is not necessarily rotationally symmetrical and invariant across the image plane. When a sensor contains a number of elements which operate serially on the signal, the aggregate point spread function tends to approach the Gaussian distribution (Figure 49).

The point spread function is an index of the image quality, including resolution, that can be obtained by a given sensor. In essence it describes the degree of signal interaction (or spillover) that takes place through the sensor. Clearly each object point contributes to the signal intensity at each image point. The relative contribution depends on the signal strength at the object point, the point spread function and the separation of the object and image points. Mathematically this is expressed as follows:

$$i(u) = k f(u) I_o \quad (1)$$

where

$f(u)$ is the point spread function,

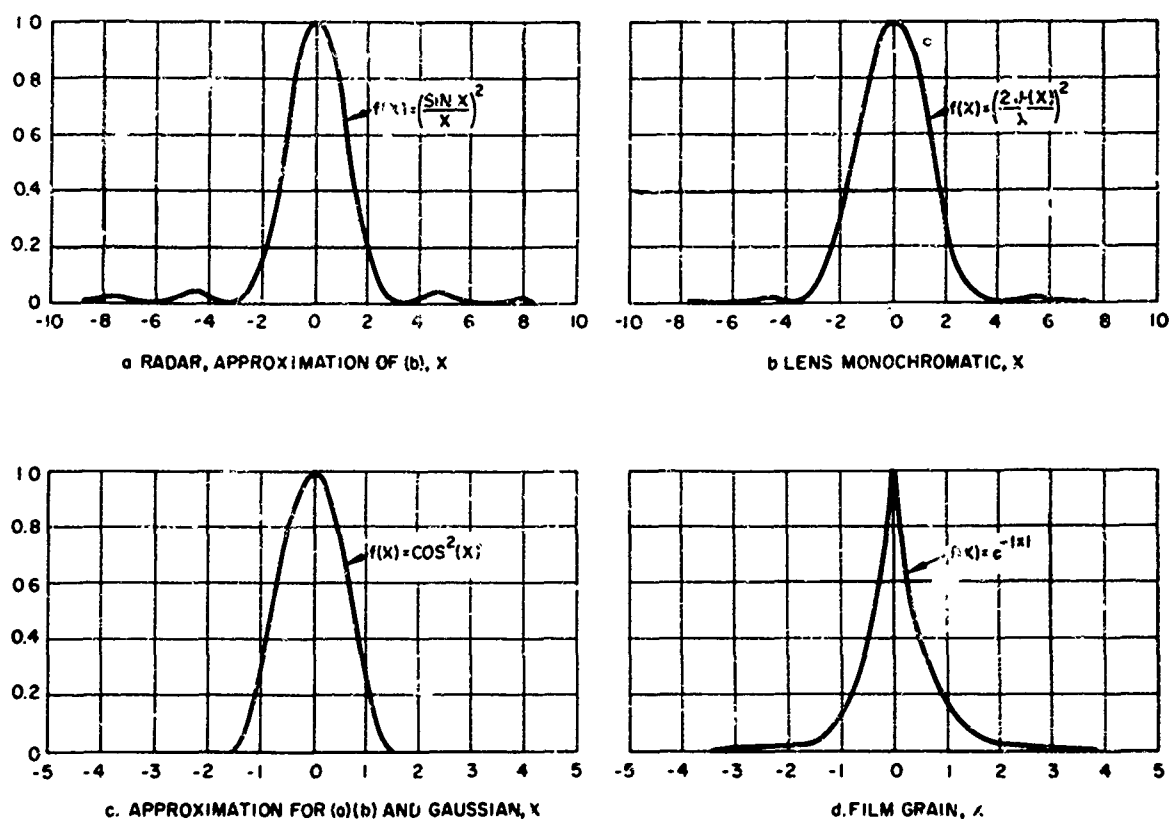


Figure 48. Representation Point Spread Functions

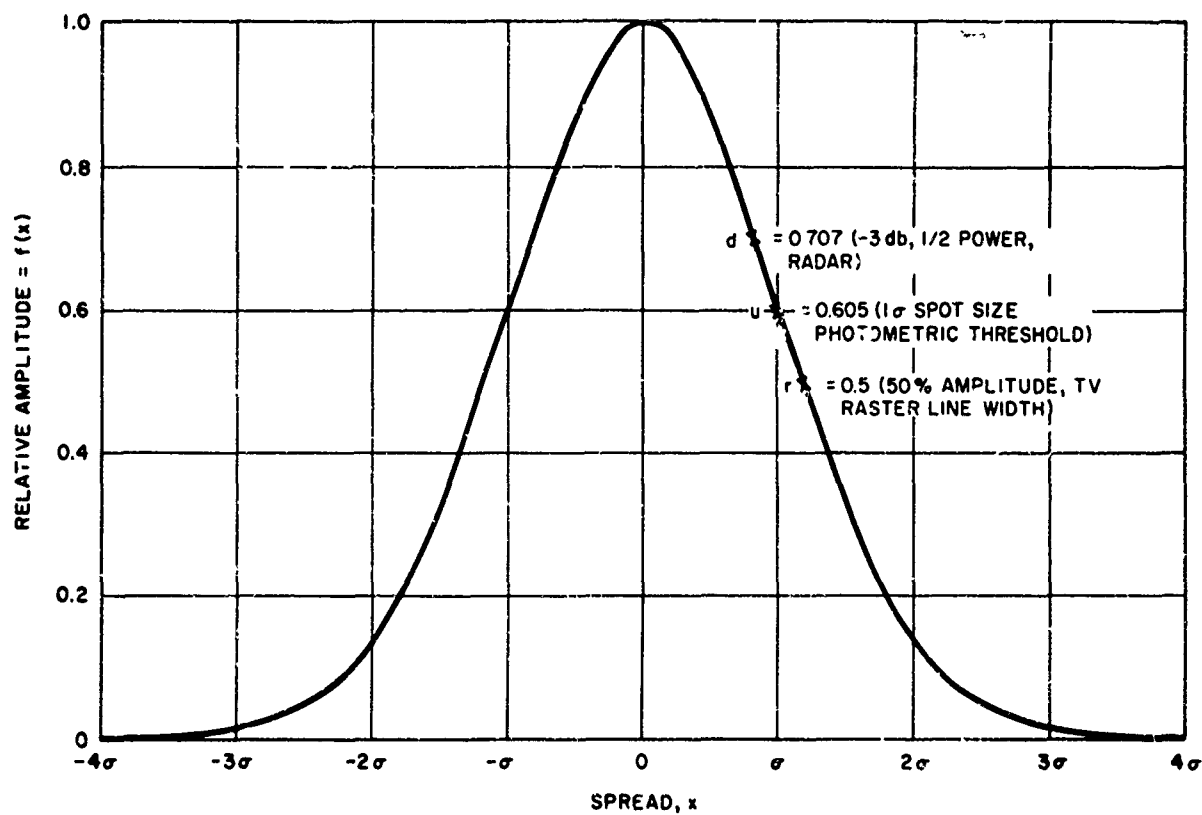


Figure 49. Normal Spread Function

I_o is the object point intensity,

u is the separation of the object point and image point, and

k is an intensity scale factor,

The total intensity at an image point is the sum of the contributions of all object points; in the limit this reduces to the convolution integral:

$$\begin{aligned} I(x', y') &= K \int_{-\infty}^{\infty} I(x, y) f(x' - x, y' - y) dx dy \\ &= K \int_{-\infty}^{\infty} I(x' - x, y' - y) f(x, y) dx dy \end{aligned} \quad (2)$$

where:

$f(x, y)$ is the two dimensional point spread function,

$I(x, y)$ is the object function, i. e. signal distribution over object space,

K is an intensity scale factor,

x', y' are the coordinates of any image point, and

integration over all object (or image) space is indicated.

In theory, substitution of the function describing a test pattern and a sensor point spread function into equation 2 results in a complete description of the image. The intensity distribution in the image obviously depends on the shape of the point spread function as well as the test pattern. Thus the appearance of the test pattern images varies across sensors. This fact is pointed out to indicate one of the limitations of the expressions derived below. Equation 2 indicates that the signal interaction is strongest when the point separation is smallest. When the spacing between two equally intense object points is infinitesimally small their images are indistinguishable. As the points separate (assuming an otherwise uniform background) there appears a dip in intensity between their geometric images (neglecting apparent resolution effects) as indicated in Figure 50. One definition of resolution is the minimum point spacing at which the dip becomes consistently noticeable. This definition includes operator judgment which was pointed out to be undesirable in an objective measure of sensor resolution. Therefore it has become customary to define resolution as the point separation at which the

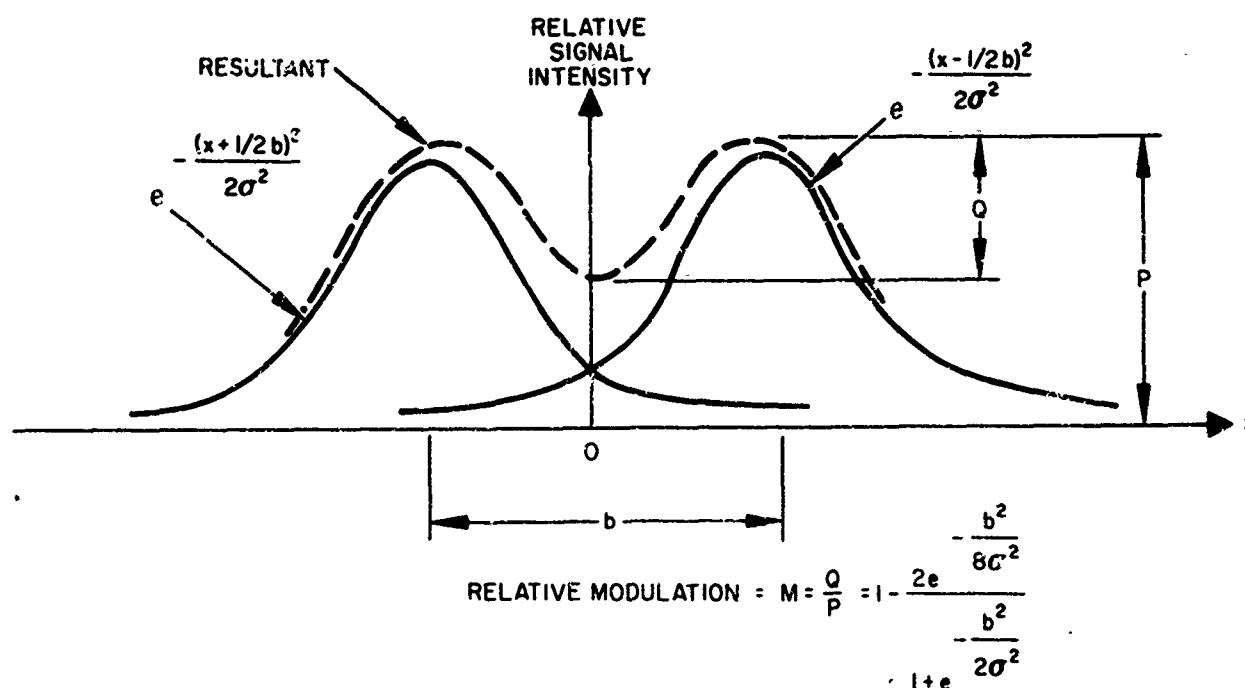


Figure 50. Formation of Point Images

contrast between the dip and the image peaks is equal to an arbitrary value. The dip contrast is popularly referred to as "modulation." Three criterion values of modulation are frequently used: 50 percent for television, 26.5 percent which corresponds to the Rayleigh criterion of optical resolution, and the photometric threshold of the human eye which is variously taken as a number between 1 percent and 20 percent depending on the application. Realization of system resolution at the lower values, in practice, is very doubtful because the photometric threshold is generally measured by comparing intensities of adjacent areas which are separated by sharp boundaries; the images of test patterns (after they have passed through sensors) are generally characterized by "soft" edges which blend gradually. This makes contrast detection much more difficult. The Rayleigh criterion is known to be somewhat liberal, particularly for point patterns where shape factors are available as clues to image separation. The 50 percent criterion is a convenient standard for comparison and measurement purposes. It lacks the threshold qualities of a true measure of resolution.

Modulation varies as a function of object separation, the point spread function, and test pattern characteristics. The Gaussian distribution is a good first approximation for the shapes of the point spread functions of a number of sensor systems. Therefore it is used as the basis for the derivation of the relationships among various measures of resolution. It should be borne in mind that the results are only as good as this approximation.

The modulation curves for a point (or line) pattern (also referred to as delta functions or impulses), parallel bars and sine waves, convolved with a Gaussian spread function (standard deviation is σ), are shown in Figures 51, 52, and 53. The image formation processes for points and extended objects are indicated in Figures 50 and 55. The basic curves shown in Figures 51, 52 and 53 are frequently plotted in terms of frequency units. Spatial frequency is merely the reciprocal of the line separation. The above curves may be more familiar in their "folded" form as shown in Figure 54. In this form they are sometimes referred to as "response characteristics." The modulation curves for sinusoids have a number of very useful and interesting properties. They have been given the special name "Modulation Transfer Function" (MTF, normally plotted against spatial frequency or lines per unit length). Without going into detail it is pointed out that, for serial components the combined MTF is found by multiplication of the individual MTF's. This property is convenient for graphical prediction of system performance where the spread functions of individual components cannot be approximated by the Gaussian distribution.

If the shape of the point spread function is known then the modulation function for any test pattern is uniquely determined if a single parameter, defining the width of the distribution, is given. Therefore resolving power is frequently defined as the width of the impulse response at a given amplitude or power level (without specifying the shape of the impulse response — the Gaussian approximation is implied).

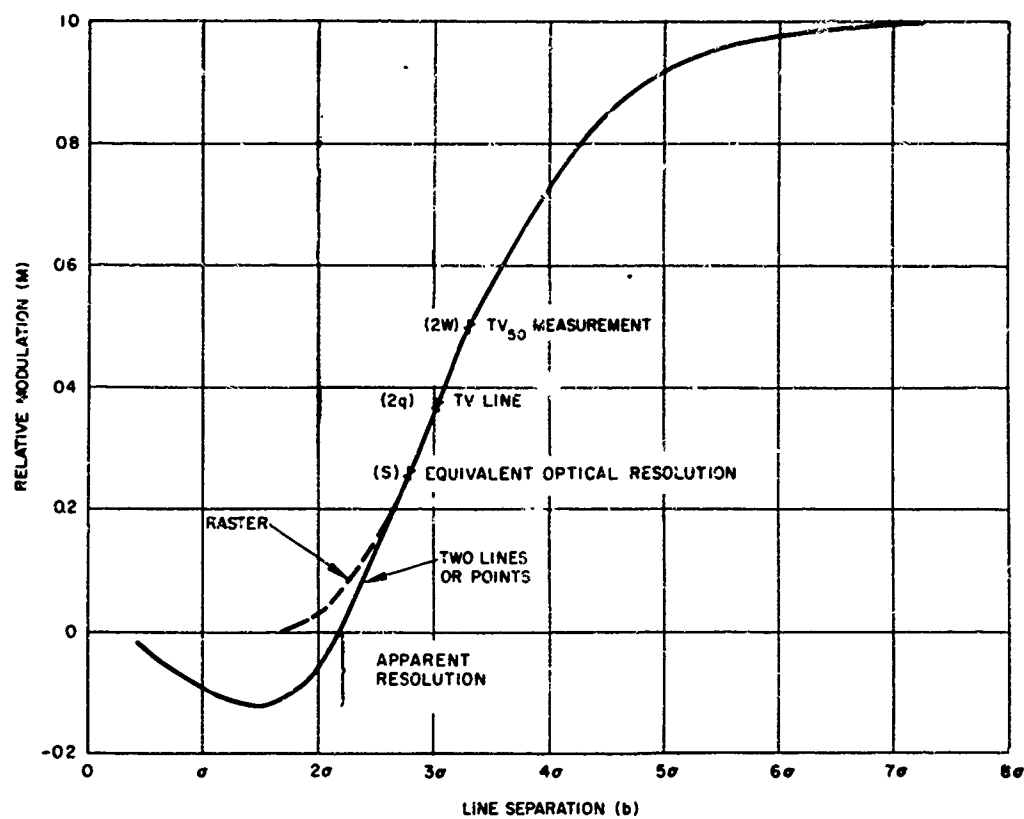


Figure 51. Impulse Modulation (Gaussian Spread Function)

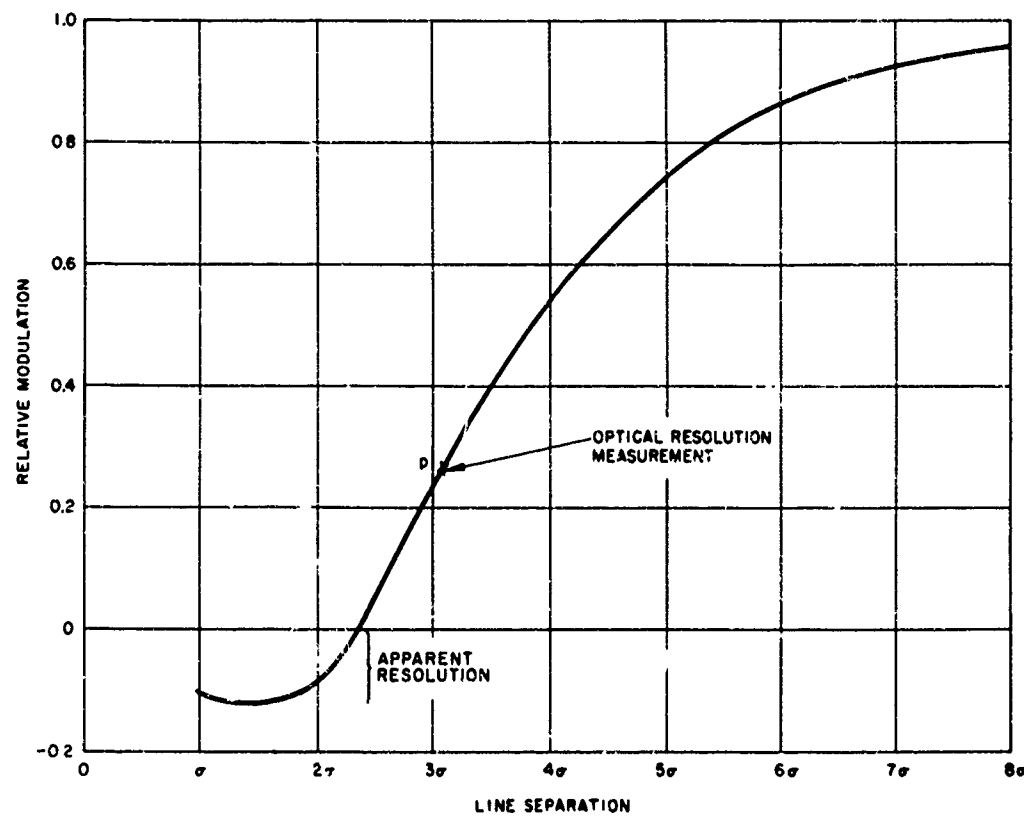


Figure 52. Bar Pattern Modulation (Gaussian Spread Function)

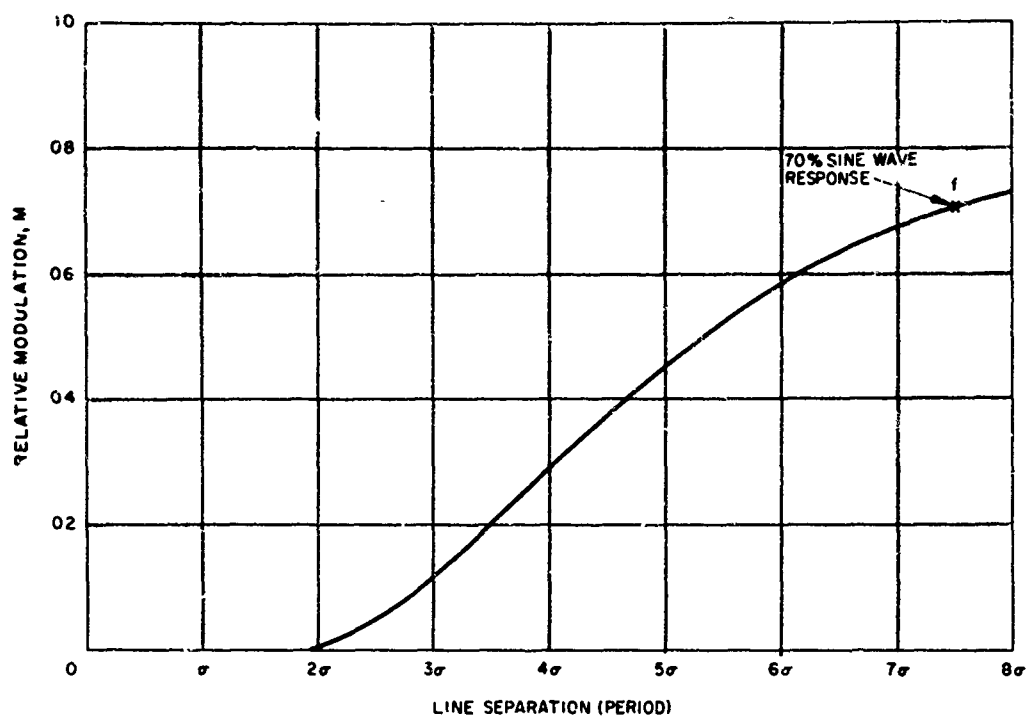


Figure 53. Side Wave Modulation (Gaussian Spread Function)

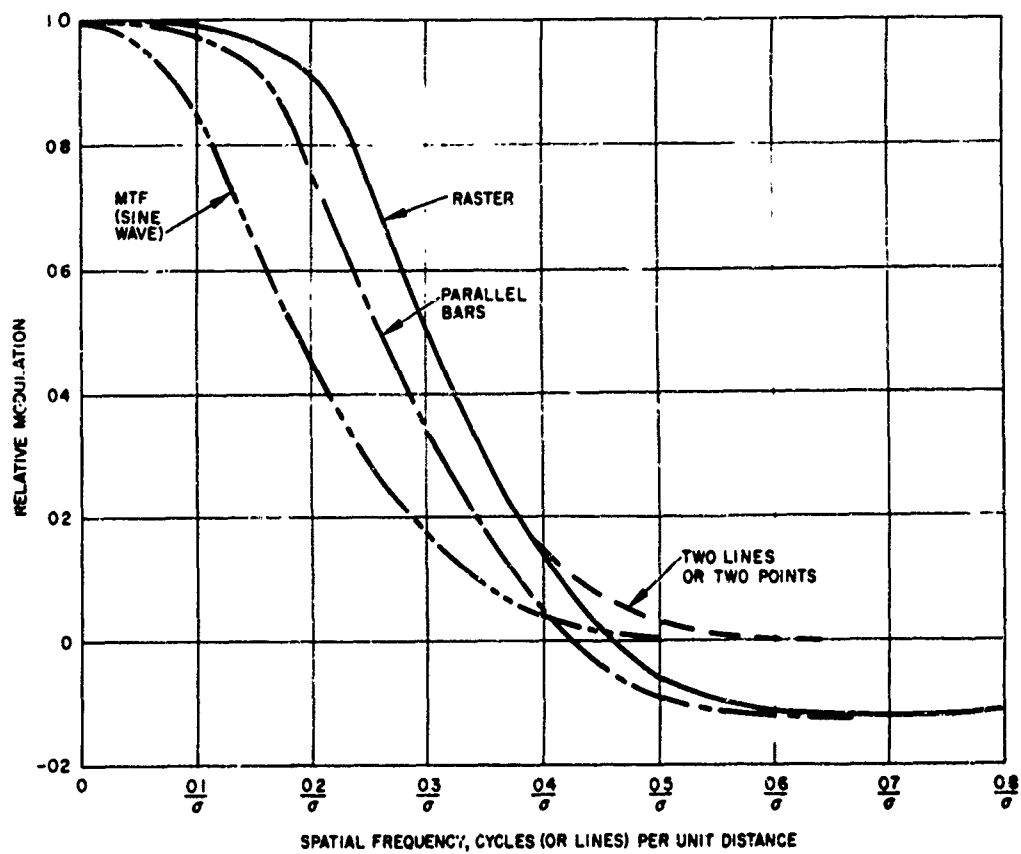


Figure 54. Relative Modulation Curves for Lines, Bars and Sine Wave Patterns

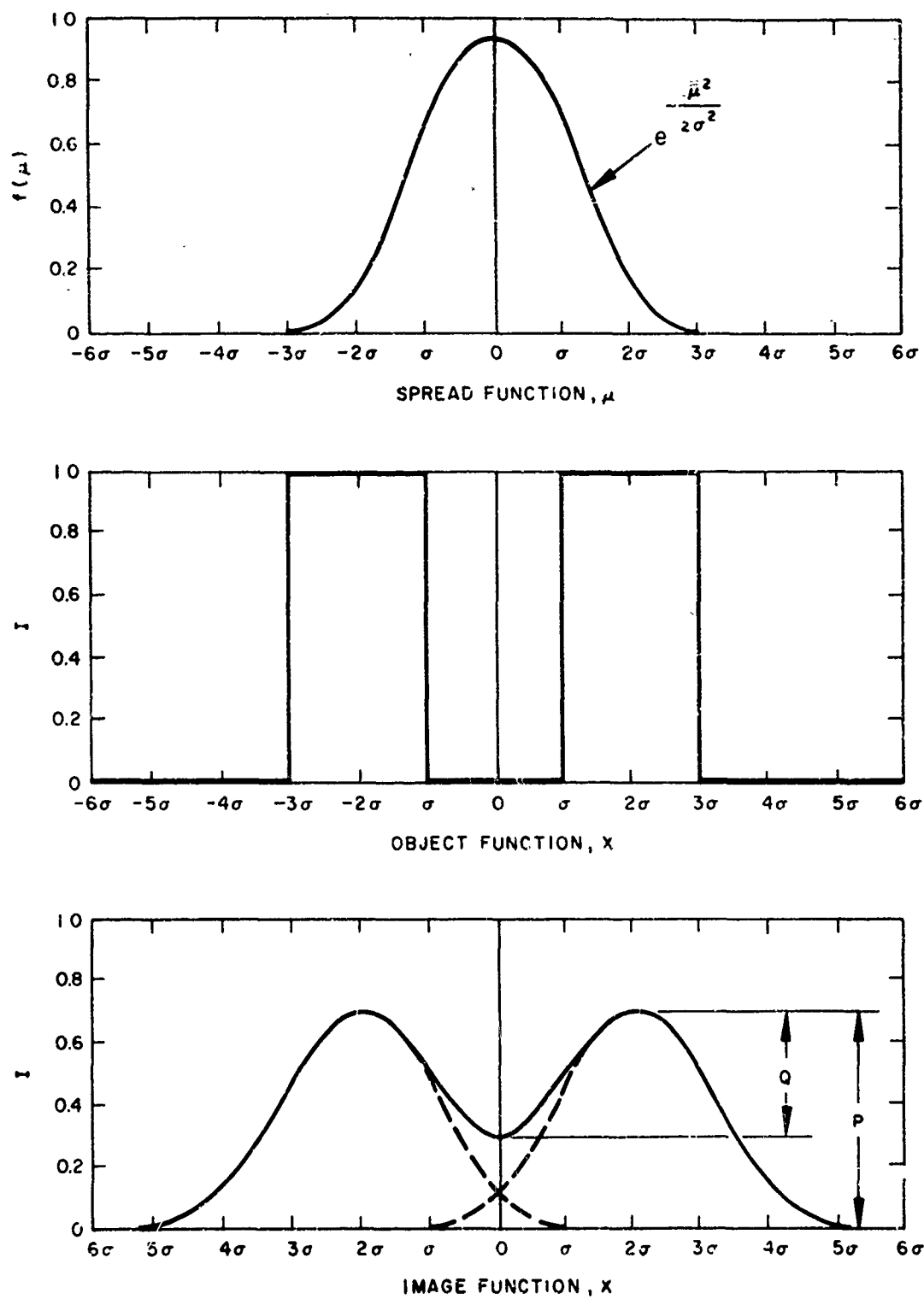


Figure 55. Formation of X Bar Pattern Image

Various criteria and measures of resolution and resolving power are indicated in Figures 49, 51, 52 and 53. They are related as follows:

$$d = 1.67\sigma = .59s = .54p = 1.11q = .71r = W = .83u = \frac{.221}{f_{-3db}} \quad (3)$$

where

- 1) d is the conventional radar resolution, also referred to as the -3db impulse response or the width of the 70 percent contour of the impulse response (Figure 49).
- 2) σ is the standard deviation of the point spread function (which is assumed to be Gaussian in this report), (Figure 49).
- 3) s is the equivalent optical spot size, also known as the $\frac{1}{e}$ spot size (line pair), (Figure 49).
- 4) p is the optical line pair resolution according to the Rayleigh criterion (Figure 52).
- 5) q is the standard TV element size (half cycle width), (Figure 51).
- 6) r is the raster line width, defined as the 50 percent amplitude contour of the impulse response, (Figure 51).
- 7) w is the TV_{50} element size (half cycle) defined by the 50 percent modulation level of the impulse pattern (Figure 51).
- 8) u is the 60 percent contour width; the MTF at this separation approximates the lowest photometric threshold of the eye; it is sometimes referred to as the 2σ spot width, (Figure 49) or shrinking raster spot size, and
- 9) Finally, f_{-3db} is the spatial frequency at which the sine wave response (MTF) is down -3db (.707), (Figure 53).

The relationships among these resolution measures and their point (or line), bar, and sinusoidal modulation values are listed in Table X.

Table X. RELATIONSHIPS AMONG VARIOUS MEASURES OF RESOLUTION

Resolution Measure	Symbol	Element or Line Pair Width	Amplitude at the Element Width	Modulation at Line Pair Separation		
				Lines or Points	Bars	Sinusoid
Radar Resolution	d	1.67σ	.707	-.11**	-.11**	0
Equivalent Optical Resolution	S	2.83σ	.368	.27	.17	.09
Rayleigh Resolution (Optical)	p	3.08σ	.33	.39	.27	.13
Standard TV Element Width	q	1.5σ	.33	.37	.23	.11
TV Raster Line Width	r	2.36σ	.500	.07	0	.03
TV50 Element Width	w	1.67σ	.24	.50	.35	.17
60 percent Spot Size (Shrinking Raster)	u	2σ	.605	-.06**	-.09**	.007
Spatial Frequency at -3db MTF level	f	7.5σ	.001	.99	.94	.707

* σ = standard deviation, Gaussian point spread function is assumed.

**Negative number implies apparent or false resolution when object separation equals one line pair.

The term resolution as used in the previous section on target recognition was defined as ground resolution which is related to photographic resolution, p, by the equation:

$$R_g = \frac{SF}{(304.8) (R_p)}$$

where:

R_g is ground resolution,

SF is scale factor,

R_p is photographic resolution (p).

and 304.8 is the number of millimeters per foot.

When defining the resolution of the display medium (the tube) the standard TV element size, q , is used.

A discussion of resolution would be incomplete without mention of techniques for determining the resolution (or more properly resolving power) of a chain of elements from the individual components. If the MTF's of the elements are known then point by point multiplication results in the aggregate MTF. Resolution is determined by reading off the spatial frequency (or line separation) at which the modulation criterion is satisfied, e. g., the equivalent of optical line pair resolution is obtained where the MTF falls to 13 percent of its low frequency value (see Table X). When the individual point spread functions can be approximated by the Gaussian distribution the combined resolution can be found by taking the square root of the sum of the squares of the component resolutions, i. e.

$$d = \sqrt{d_1^2 + d_2^2 + \dots + d_n^2} \quad (4)$$

The resolution values used in equation (4) must all be defined at the same amplitude level of the point spread functions. Sometimes conversions are necessary. The proof of equation (4) proceeds as follows:

Let

$$f_i(X) = \frac{1}{\sqrt{2\pi} \sigma_i} e^{-\frac{x^2}{2\sigma_i^2}}$$

be the point spread function of the i th system component (scaled by a factor of $\frac{1}{\sqrt{2\pi} \sigma_i}$). The input sinusoid is convolved in turn with the spread

function of each element. The Fourier transform of a convolution integral is the product of the Fourier transforms of the individual elements:

$$F_t(\mu) = F_1(\mu) F_2(\mu) \dots F_n(\mu)$$

the transform of $f_i(x)$ is

$$F_i(\mu) = \int_{-\infty}^{\infty} f_i(X) e^{-\mu x} dx = e^{-\frac{\mu^2 \sigma^2}{2}}$$

therefore

$$F_t(\mu) = e^{-\frac{\mu^2}{2} (\sigma_1^2 + \sigma_2^2 + \sigma_3^2 + \dots + \sigma_n^2)}$$

the inverse transform of $F_t(\mu)$ is

$$f_t(X) = F_t^{-1}(\mu) = \frac{1}{2\pi} \int_{-\infty}^{\infty} F_t(\mu) e^{i\mu x} d\mu$$

substitution of $F_t(\mu)$ results in

$$f_t(x) = \frac{1}{\sqrt{2\pi} \sqrt{\sigma_1^2 + \sigma_2^2 + \sigma_3^2 + \dots + \sigma_n^2}} e^{-\frac{x^2}{2(\sigma_1^2 + \sigma_2^2 + \sigma_3^2 + \dots + \sigma_n^2)}}$$

Comparison of f_t with f_i shows that the two functions have the same shape and that the equivalent standard deviation of f_t is the square root of the sum of the squares of the individual deviations. Since the resolution element size is defined at a constant level it can be equated to a σ within a multiplicative constant. Hence Equation (4) follows immediately from the last expression above.

It has been pointed out repeatedly that the relationships contained in Table X and Equations (3) and (4) are only valid when the Gaussian approximation of the impulse response is valid. It has been estimated that the relationships are correct within ± 10 percent for all common sensors. Other limitations include: (1) the point spread functions must be approximately constant across the image plane and they must be very nearly rotationally

symmetrical, (2) linear sensor operation is assumed; highly non-linear operation (e.g., limiting or saturation) renders the results invalid (over the image regions where they occur). Thus the relationships presented in this report can only be used as first approximations. When accurate data is desired, detailed analysis or laboratory measurements is necessary.

The use of the expressions derived above is illustrated by means of examples:

Example 1: Suppose radar resolution is quoted as $d = 15$ ft. (- 3db) impulse response. The equivalent optical resolution from Equation (3):

$$p = \frac{d}{.54} = 28.8 \text{ ft.}$$

Example 2: For the radar resolution of Example 1 the minimum object separation is desired. Assuming that the Rayleigh criterion applies and the objects can be approximated by a bar pattern then the minimum resolvable object separation is 28.8 ft. If the photometric threshold is taken to be 5 percent then, from Figure 52 this minimum resolvable bar separation, x , is about 2.5 σ . From Equation (3)

$$d = 1.67\sigma = 15 \text{ ft (from above);}$$

therefore,

$$x = 2.5\sigma = \frac{2.5d}{1.67} = 22.5 \text{ ft.}$$

at the 1 percent modulation level $x = 2.38\sigma = 21.4$ ft.

Example 3: The modulation corresponding to the equivalent optical line separation is 27 percent. At the same separation, bar and sine wave modulation are 17 percent and 9 percent respectively. If the former is barely visible the latter will probably not be resolved.

Example 4: The TV_{50} element width corresponding to 15 ft. radar resolution is 15 ft. (from Equation 3, $w = d$). Therefore, (neglecting the Kell factor) the equivalent TV resolution is 15 ft. Similarly, if optical resolution is $p = 15$ ft. then to achieve equivalence the nominal TV_{50} resolution is $w = .54 p$ (from Equation 3) = 8.1 ft.

Example 5: Suppose the MTF is down -3 db at $f = \frac{1}{30}$ line/ft., from Figure 53 the line separation corresponding to -3 db is $7.5\sigma = \frac{1}{f}$, $\therefore \sigma = 4$ ft. and the equivalent optical resolution (from Table X) is

$$p = 3.08\sigma \doteq 12.3 \text{ ft.}$$

and radar resolution

$$d = 1.67\sigma \doteq 7.7 \text{ ft.}$$

(alternatively Equation 3 could be used without first determining σ).

Example 6: It is desired to determine equivalent visibility conditions for lines, bars, and sinusoidal test patterns. At high spatial frequencies (small separation) the shapes of the images of the three test patterns approach each other. Therefore, equal visibility is implied by equal modulation. Read across Figure 55 to obtain the spatial frequencies corresponding to a given modulation.

Example 7: It is required to determine the frequency response required to transmit a 1 x 1 n. mi. radar frame with 15 ft. resolution in $\frac{1}{30}$ sec. From Example 4 the equivalent TV_{50} resolution is 15 ft. Assuming that a scanning technique is used then a factor of .7 must be introduced to account for the raster structure. This is the familiar Kell factor. The frequency required is

$$f_R = \frac{6080}{15} \times \frac{6080}{15} \times \frac{1}{.7} \times \frac{1}{\frac{1}{30}} = 7 \times 10^6 \text{ cps} \doteq 7 \text{ mc}$$

If optical resolution is quoted as 15 ft., then from Example 4 the equivalent TV_{50} resolution is 8.1 and the frequency required for transmission of a 1 x 1 mi. area in $\frac{1}{30}$ sec. is

$$f_P = \frac{6080}{8.1} \times \frac{6080}{8.1} \times .7 \times \frac{1}{\frac{1}{30}} = 24.2 \text{ mc}$$

DISPLAY SIZE

Ignoring for the moment constraints imposed by aircraft structure and space limitations, the ideal display size may be estimated by any of several methods. For the VSD panel mounted displays the size will be determined by the required field of view, the magnification, and the observer viewing distance. For the map displays, consideration must be given to scale and chart coverage. For the sensor displays the ideal size may be calculated by considering the sensor capacity, the display resolution, and the limit resolution of the eye. In order to clarify these statements sample cases for the VSI and sensor displays will be worked out.

Let us examine the case for a panel mounted contact analog. For operational reasons the field of view should be on the order of $\pm 30^\circ$ in azimuth and $+15^\circ$ to -20° in elevation. To preserve sensitivity in the display and prevent too severe a distortion, the magnification range is limited to 0.33 to 2.0. At 24 inches viewing distance the above field of view at a magnification of 0.5 results in a display whose linear dimensions are approximately 14 x 8 inches. (The linear size required for various fields of view and viewing distances is shown in Table XI.) At this same viewing distance and size a display with 560 resolution elements (TV resolution, q , equals about 1100 lines) will provide a resolution that is not display limited. (See Figure 39.) For this particular display as well as the TV display when used for flight control, it is desirable to have more resolution in the elevation than in the azimuth dimension by a ratio of about 2:1. Therefore, if a trade-off must be made, azimuth resolution should be sacrificed in favor of elevation resolution.)

Table XI. DISPLAY SIZE VS FIELD OF VIEW
Viewing Distance, Inches

		12 Inches	18 Inches	24 Inches	30 Inches
Field of View	5°	1.05 inches	1.57 inches	2.10 inches	2.63 inches
	10°	2.10 inches	3.15 inches	4.20 inches	5.26 inches
	15°	3.16 inches	5.74 inches	6.32 inches	7.90 inches
	20°	4.23 inches	6.34 inches	8.46 inches	10.58 inches
	25°	5.32 inches	7.98 inches	10.64 inches	13.30 inches
	30	6.43 inches	9.64 inches	12.86 inches	16.08 inches

Required Display Size for VSD
(Unit Magnification)

For a sensor display it is desirable that sensed information not be thrown away. Therefore the resolution capacity of the display should be about double that of the sensor if both resolutions are measured identically. If they are not measured identically conversions are provided in the section on "resolution". If, then, the display resolution is set equal to the limit eye resolution then the display size can be calculated for any given viewing distance. Some displays serve sensors that accumulate information relatively slowly. The modulation along a line as well as required field of view dictate size in this instance.

Each of the displays is susceptible to this form of analysis, and a chart illustrating the consequences of such calculations is shown in Table XII. Some other display requirements have been added to the chart in order that all the information appears at one place. Examination of this chart shows a tremendous conflict in requirements depending on the intended use of the display. To design a single display device that would satisfy all these requirements seems a Herculean task. The range of brightnesses, the extreme resolution requirements, the range of writing speeds and storage times places severe demands on any combination of displays, much less a single device.

Table XII. SOME REQUIREMENTS FOR PICTORIAL DISPLAYS

Representative Values for Raster Scan Display Requirements												
Display Type	Sensor	Nominal Sensor Characteristics		Field of View	Magnification Range	Approximate Size (1)	Data Rate Cps	Writing Speed and Field Rate	Storage Time Seconds	Resolution, q_v (Standard TV Lines or Equivalent) (1)	Shades of Gray (Minimum)	Brightness Range on Tube for 2000 ft Ambient (10% Filter)
Skeletal Vertical Situation	N.A.	Frame Rate Cps	Resolution Elements/Diameter (d)	Minimum: AZ = $\pm 20^\circ$ EL = $\pm 15^\circ$ to -20°	Limits: 0.33 - 1.0	Magn. 0.33 1.0 AZ: 6" 17" EL: 5" 15"	Translation: 50 cps Rotation: 60 cps	TV Rates	Translation: 0.033 Rotation: 0.016	Magn. 0.33 1.0 AZ: 840 2400 EL: 700 2000	2	140-400 FIL
		N.A.	N.A.	Minimum: AZ = $\pm 30^\circ$ EL = $\pm 15^\circ$ to -20°	Limits: 0.33 - 2.0	Magn. 0.33 2.0 AZ: 8" 50" EL: 5" 30"	Translation: 30 cps Rotation: 60 cps	TV Rates	Translation: 0.033 Rotation: 0.016	Magn. 0.33 2.0 AZ: 1100 7000 EL: 700 4000	5	140-3200 FIL
Literal Vertical Situation	(See Below)	(See Below)	(See Below)	Minimum: AZ = $\pm 15^\circ$ EL = $\pm 15^\circ$ to -20°	Probable Value: 1.2	AZ: 15" EL: 18"	30 cps	TV Rates	(See Below)	AZ: 2000 EL: 2500	5 - 7	140-2200 FIL 140-12800 FIL
Map, Horizontal Situation	N.A.	N.A.	N.A.	N.A.	N.A.	8"	N.A.	TV Rates	N.A.	1100	3	140-800 FIL
Pattern Sensor, Horizontal Situation (also applies to literal vertical where appropriate)	Low PRF Air-to-air Doppler Radar (Synthetic Processing)	0.36	575	N.A.	N.A.	4.5"	N.A.	TV Rates	2.8	650	3	140-800 FIL
	Low PRF Air-to-air Radar	0.33 0.33	1460 185	N.A. N.A.	N.A. N.A.	11" 1"	N.A. N.A.	TV Rates TV Rates	3.0 2.0	1600 200	3 3	140-800 FIL 140-800 FIL
	Air-to-air IR, C-scan	0.16	4300			28"		TV Rates	6.0	4700	3	140-800 FIL
	Low PRF Radar Ground Map	0.33 0.33	1000 625	N.A. N.A.	N.A. N.A.	8" 5"	N.A. N.A.	TV Rates TV Rates	3.0 3.0	1100 587	5 - 7 5 - 7	140-3200 FIL 140-12800 FIL 140-3200 FIL 140-12800 FIL
	Radar GMTI	0.36	575	N.A.	N.A.	4.5"	N.A.	TV Rates	2.8	650	3	140-3200 FIL 140-12800 FIL
IR Ground Map	Side Looking Array Radar	Single Frame	690			5.5"	N.A.	TV Rates	1.0	760	5 - 7	140-3200 FIL 140-12800 FIL
Television - Standard Improved	Synthetic Processing Real Beam		280 440			2" 3.5"		TV Rates TV Rates	42.0 60.0	310 480	5 - 7 5 - 7	140-3200 FIL 140-3200 FIL 140-12800 FIL
	Television - Standard Improved	30 30	500 1000			4" 8"		TV Rates TV Rates	0.033 0.033	550 1100	5 - 7 5 - 7	140-3200 FIL 140-3200 FIL 140-12800 FIL
HUD	N.A.	N.A.	N.A.	AZ: $\pm 15^\circ$ EL: $\pm 5^\circ$ to -20°	1.0	N.A.	30	TV Rates	0.033	N.A.	2	140-3200 FIL

(1) All size and resolution estimates based on 24" viewing distance

(2) Estimated from required display size

(3) Estimated from sensor resolution

(4) In a tradeoff, consideration should be given to making the elevation resolution something like twice the azimuth resolution in both the "sensor" and display because for forward looking devices range loss due to foreshortening compression on the elevation axis takes place very rapidly

(5) Estimated from display resolution

Not considered here, of course, are practical questions of size, weight, cockpit space, and the state of the art. What must be done in a real operational system is to make compromises and trade-offs that will result in designs that can be physically incorporated in actual avionics systems. For these practical reasons the display sizes in almost all the displays previously pictured have been compromised to meet the practical objection that the ideal display would not fit in the cockpit. One must simply accept the consequence that performance using such compromised displays will be less than ideal. The ideal resolution requirements must also be altered to fit reality, and a display resolution, q , of 1000 lines has been chosen as a reasonable compromise between what is currently available and what is really needed. The contrast, brightness, and field rate requirements are less amenable to manipulation, for if the image can't be seen or flickers objectionably, the display is useless. Departures from the ideal in these instances is much more hazardous.

This chart, then, stands as an estimate of ideal requirements and one can, when designing real systems, note how far design choices depart from the ideal. The difficulty is that the performance decrement associated with exceptions to the ideal are impossible to calculate except in the instances already noted. Nevertheless, this information should further the cause of putting the selection of display characteristics on more rational grounds than is often the case.

DISPLAY DEVICES

POSSIBLE APPROACHES

In order to satisfy the specific display quality requirements derived in previous sections of this report, many approaches to the physical design of displays must be entertained. Although it is clearly beyond the scope of this discussion to examine each of these approaches in detail, our analysis to follow will of necessity involve trade-offs that can only be made on the basis of considerable knowledge of the capabilities of each approach. We must therefore examine the more important features of each of the candidate approaches. If in the interests of brevity sufficient detail cannot be presented, every effort will be made to provide references to original work so that the interested reader may pursue the subject further.

Turning to the task in hand, the factors of prime importance will be brightness, resolution, bandwidth or data rate, and gray scale or dynamic range. We would like to provide an 8-inch diameter TV-type display of such quality that little or no performance decrement would result from using it at normal close viewing distances. For the sake of discussion let us arbitrarily assume this would require 1000 lines resolution and a capability of five or more half-tone steps with highlight brightnesses in the region of one thousand or more foot lamberts and/or radical contrast improvement in order that it may be viewed in high ambients. And finally, it must be capable of TV bandwidths and frame rates. Let us now look into the possible ways of meeting these objectives.

High Brightness Direct View CRT's

The high brightness direct view CRT has been the generally preferred approach throughout the years. Although some of the newer approaches are making rapid advances, from the discussion that follows it will be evident that the high brightness direct view CRT is still the most promising display device for many applications. Since we will be treating this device in considerable detail later, let us simply summarize its properties for the moment. It is well adapted to raster scan. (Zworykin and Morton, 1954, p. 290-291.) Its theoretical limitations are well known (Langmuir, 1937; Jacob, 1939; Ramberg and Morton, 1939; Pierce, 1939). We understand the interrelationship of the many factors governing the performance of electron guns in CRT's (Law, 1942) so that we can readily scale from one design to another. We have detailed knowledge of the factors influencing contrast in devices of this kind (Law, 1939). This enables us to predict the gray scale capability and dynamic range that we may expect to achieve with a given design under prescribed conditions. We know enough about the properties of phosphors to design successful devices (Levering, 1950; Levi, 1963; Pfahnl, 1961; Studer and Cusane, 1955). And finally, we have broad experience in the design of high-beam-current high-resolution devices (Law, 1937; Schlesinger, 1961; Schlesinger, 1962).

As will be brought out in considerable detail in a later section, Specific Design, on the basis of this background and certain recent developments, there is every reason to believe that a properly designed 8-inch diameter direct view CRT operating at 30 KV can be made to give an excellent 1000 line resolution picture with highlight brightnesses in the 20,000 foot lamberts range.

Storage Tubes

Direct view storage tubes offer many advantages in some display applications. Since the incoming signal is deposited as an electron image on a separate storage surface that serves to control a continuous flood electron beam it is relatively easy to achieve high light output. The ITT

Farnsworth, commercially available 1A08P20-3 4-inch diameter Iatron is rated at a brightness of 15,000 foot lamberts. Unfortunately its resolution is only a few hundred lines. Efforts to improve the resolution of this device as required for the single-seat A7A (VAL) carrier-based attack plane and for helicopters to enable pilots to view radar data in a high-ambient-light environment under Navy contract NObsr 87264 have resulted in some improvement in resolution but at the expense of brightness. The compromise elected here is 1000 foot lamberts highlight brightness at 65 to 100 lines per inch. Another disadvantage is that the high brightness storage tube is not well adapted to presentation of rapidly changing data.

For rapidly changing data the Hughes 10-inch H-1059BP20 Multi-Mode Tonotron (Lehrer, 1961) offers many advantages. In this storage tube the writing beam serves to write, to erase, or to present non-stored information according to the energy with which it strikes the storage surface. This comes about because secondary emission charges the storage surface positively, whereas bombardment-induced conductivity charges it toward the backing plate potential. Since secondary emission predominates at lower energies, the target is written on in the one case. Since bombardment-induced conductivity predominates at higher energies, the target is erased in the other case. Furthermore there is an intermediate energy where the two effects just balance, and non-stored information may be displayed. Thus any desired effect may be selected at will. The resolution and brightness of the proposed 12-inch (10-inch diameter viewing screen) Multi-Mode Tonotron are in the range of 1100 lines resolution and 300 foot lamberts highlight brightness. Unfortunately the erasure speed may still not be adequate for TV-type displays and non-stored TV operation reduces brightness.

Light Valves

This type of device is attractive because the light intensity is not directly limited by the power capability of the scanning electron beam. A variety of light valves have been proposed over the years. Some of the earlier systems such as the supersonic light valve Scophony system

(Lee, 1938) which involves rapidly rotating mechanical parts or the Suspension Light-Valve (Donal, 1943) system using graphite flakes suspended in a liquid medium to control the passage of light are hardly appropriate to this discussion, but the more recent systems such as the deformable surface light valve, the electro-optic media light valve, and the magnetic reflective effects light valve which are presently under continuing development, deserve consideration.

The principle of the deformable surface light valve as exemplified by the Eidophor system (Thiemann 1949) used for large screen television projection is potentially applicable to our purposes. However major engineering problems require solution for airborne application. Although the military systems developed by General Electric are ponderous, involving racks of equipment and requiring continuous vacuum pumping, a more recent contractual effort supported by the Navy under contract NObsr-39400 for a sealed-off light valve could lead to a practical device. In the large size military unit the projector gives an output of 1800 lumens in monochrome and 350 lumens in field sequential color. Depending upon the diffuser employed to control the viewing angle, the brightness would be somewhat reduced. In the case of a perfect transmission, perfect diffusion viewing screen, brightness would be reduced by a factor π to give approximately 600 foot lamberts highlight brightness in the monochrome picture. The observed resolution in these devices is of the order of 500 lines. It is not known whether greater resolution can be easily achieved.

Electro-Optic light valves have also been widely used over the years (Zworykin, 1954). A crystal plate of ammonium dihydrogen phosphate ($\text{NH}_4\text{H}_2\text{PO}_4$ or ADP) is employed as a light valve. The scanning electron beam develops an electrical potential across the corresponding plate which changes the velocity of propagation of the ordinary and extraordinary light rays causing modulation of the polarized light. This system is currently being re-examined by the Air Force at Autonetics under Air Force contract AF 30(602)-3263-RADC. Experimental tubes have been delivered. Images have been observed, but this does not seem to be a serious contender for the present system.

Light Reflection approaches of several kinds are currently being investigated. Under Navy contract NObsr-91199 the Laboratory for Electronics is investigating the changes in reflectivity of thin magnetic films containing fine particles in colloidal suspension as controlled by magnetic field effects. Another approach has been the chemical electro-deposition of a reflective film as exemplified by work at Aeronutronics under Air Force contract AF 30(602)-3010-RADC. Although these variable reflection devices have potential future interest, their present capability is to barely produce an image and they are certainly not contenders for the present system.

Photochromic Dyes may also be used as a light valve. They are transparent themselves until they undergo a color change upon activation by ultraviolet light. The light activator can be derived from a CRT with a flying-spot scan, a laser, or a mechanically deflected beam from a lamp. When the activation light is removed the induced color can be made to fade at a rate which is controllable and the reversible color change can be repeated many times. The colored portion appears as a dark area on a display screen. The optical density, the color, the rate of fade or persistence, depends on the intensity and spectral distribution of the activation light on the temperature of the layer and on the characteristics of the material. A considerable range of persistence and colors are presently available but this approach is hardly a contender for the present system.

Lasers

There is no doubt that lasers will play an important role in future display devices. Because their light output is highly collimated it may be conveniently directed in a single direction. The problem is to deflect the light beam over the raster. Deflection by acoustic means (Giarola and Billeter, 1963, p. 1150-1151) was suggested soon after the laser became available. Tests on systems of this kind were soon thereafter reported by Bell Telephone Laboratory workers (Cohen and Gordon, 1964). Electro-optic means have also been used to deflect laser beams. The variation of Pockels electro-optic effects in crystals such as KH_2PO_4 gives rise to

useful deflection when high electrical potentials are applied (Fowler, Buhrer and Bloom, 1964, p. 193-194). Unfortunately the acoustic and electro-optical deflection means are all limited to relatively small deflection angles and correspondingly few element diameters. At best these systems appear to be capable of resolutions of only a few hundred lines.

The only promising laser deflection system so far developed has been the psuedo-mechanical system developed by Texas Instruments for RADC under Air Force contract AF 30(602)-3271. In this system a 100 milliwatt cw laser is modulated by a KDP modulator. The modulation beam is horizontally scanned by a spherical mirror which focuses it onto a piezoelectric-driven fiber-optic scan converter. The beam is next directed to the mirror of a galvanometer-vertical scanner and then through a projection lens to a screen. With a F2 5.5-inch focal length projection lens, a 5-foot lambert highlight brightness picture is obtained on a one meter square viewing screen. The resolution is approximately 525 x 525 lines. Translated to a picture size of 6 inches x 6 inches, this corresponds to a highlight brightness of 250 foot lamberts. Since CW lasers giving power outputs up to 5 watts, either are or soon will be available, this means that highlight brightnesses of the order of 10,000 foot lamberts may become feasible.

Other Possible Approaches

For the sake of completeness, consideration must also be given to electroluminescent devices. Electroluminescent panels may ultimately have a number of advantages but are probably not important in this survey because of their relatively low brightness and the necessity of matrix switching. At best their brightness is limited to a few hundred foot lamberts and switching requires relatively high voltages. The low brightness stems from the lack of persistence. To be successful, such devices will require the additional feature of a storage element. Much work is going on in this area and panel-type display devices will undoubtedly become important in the future.

Injection electroluminescence, or semiconductor luminescence is similar to that of injection lasers except that coherent light is not required. Photons are produced in semiconductors through electrical injection of

minority carriers and their decay by radiative recombinations. It is achievable by forward biasing of p-n junctions. Injection electroluminescence will undoubtedly become important in the future for it has a number of advantages. It uses low voltages, in the order of 2-10 volts, which is readily obtainable from semiconductor matrix switching devices. Very high light intensity, up to thousands of foot lamberts, are technically possible at relatively high efficiency. Selection of colors should soon be available. However, the technology is in an earlier stage of development and it will be several years before any useable devices are ready for experimental evaluation much less ready for system applications. Also there is the problem that the discrete elements must be excited by a matrix arrangement rather than by a raster scan. This effectively removes it from consideration in the present instance.

PREFERRED APPROACH

On the basis of the foregoing survey of possible approaches it is clear that the high brightness direct-view CRT is still the most promising display device for the present application. To emphasize this point the table below shows the relative performance of the several possible approaches as related to highlight brightness and resolution. Also included are other relevant remarks for each device.

POTENTIAL CAPABILITIES

Approach	Highlight Brightness	Resolution	Remarks
Direct View CRT	20,000 ft.L.	1000 lines	Conventional approach
Laser	2,000	1000	Pseudo-Mechanical Early state of development
Light Valve	1,000	500	Complex
Storage Tube	300	1000	May be difficult to erase

It should be emphasized that considerable judgement is required in relating highlight brightness and resolution in each of the systems, particularly in the case of the laser system. The projected values are optimistic and presume that the system will not fail by overheating and that the present 525 x 525 line system can be scaled into a 1000 line resolution system. Similar arguments apply to the tabulated data for storage tubes. Storage tubes with brightnesses of 10,000 foot lamberts are available but the resolution is inadequate and they cannot be erased. Only the Multi-Mode Tonotron capability for rapid erasure can be considered in this instance and projected tubes of the future have a highlight brightness in the range of 300 foot lamberts at TV speeds and a resolution in the range of 1000 lines.

With a 20,000 foot lambert highlight brightness direct-view CRT we should be able to do quite well even under the most unfavorable ambient of direct sunlight. If we assume that direct sunlight illumination is 10K foot candles and that the CRT reflectance is 0.5 without a filter covering the CRT, the best we could do would be highlights 20K foot lamberts and lowlights 5K foot lamberts for a contrast ratio of 1. However, with a 0.2 transmittance filter over the CRT we could have highlights of 4K foot lamberts and lowlights of 200 foot lamberts for a contrast ratio 20. The relationship of contrast ratio to filter transmittance is clearly indicated in the following table:

Filter Transmittance per cent	Contrast Ratio	Apparent Highlight Brightness ft. lamberts	Apparent Lowlight Brightness ft. lamberts
100	4	20,000	5,000
30	13	6,000	450
20	20	4,000	200
10	40	2,000	50

SPECIFIC DESIGN

Langmuir (1937) has shown from the basic laws of electron optics that the ultimate ratio of current density at the screen to that at the cathode in an electron beam forming device is

$$\frac{j_s}{j_o} = (1 - E \frac{e}{KT}) \sin^2 \left(\frac{\theta}{2} \right) \quad (1)$$

Where:

j_s = current density at the screen

j_o = current density at the cathode

E = beam voltage

e = electronic charge

K = Boltzmann's constant

T = absolute temperature of the cathode

θ = beam angle

Pierce (1949, pp 116-144) has shown that this ultimate cannot be realized but that a compromise must be made between intensity efficiency and current efficiency. More specifically, two-thirds of the above density-gain can be realized if 40 percent of the total current emitted is sacrificed. With these factors, equation (1) transforms into

$$I_b = 0.6 d^2 j_o E \frac{e}{KT} \sin^2 \left(\frac{\theta}{2} \right) \quad (2)$$

Where:

I_b = beam current

d = spot diameter

To achieve the greatest possible cathode current density we would use a dispenser type cathode and operate with an emission density in the range of 2.0 amp/cm^2 . To achieve the largest possible $\sin^2 \left(\frac{\theta}{2} \right)$ we would employ magnetic final focusing with a specially shaped lens (Law 1937). Although final focusing may be accomplished by either magnetic or retarding type electrostatic lenses, Law (1937) found experimentally that larger

aberration-free apertures could be obtained with magnetic lenses than with conventional concentric cylinder electrostatic lenses. The reason for this is simple. Although the aberration-free aperture of conventional concentric cylinder lenses may be increased by enlarging the lens this is only accomplished by a sacrifice in magnetic deflection sensitivity which depends upon the bulb-neck diameter. Magnetic lenses located outside the tube envelope are not restricted by bulb-neck diameter and may therefore be made sufficiently large to give aberration-free apertures several times greater than conventional concentric cylinder electrostatic lenses. With the magnetic final focusing lens and electron gun illustrated in Figures 56 and 57 below taken from that reference, it was possible to compress a 2.0 ma beam through a 0.004 inch diameter aperture at 10 kv with an emergent beam angle of approximately 6° and then image this beam onto a viewing screen 220 mm away into a spot 0.010 inches in diameter.

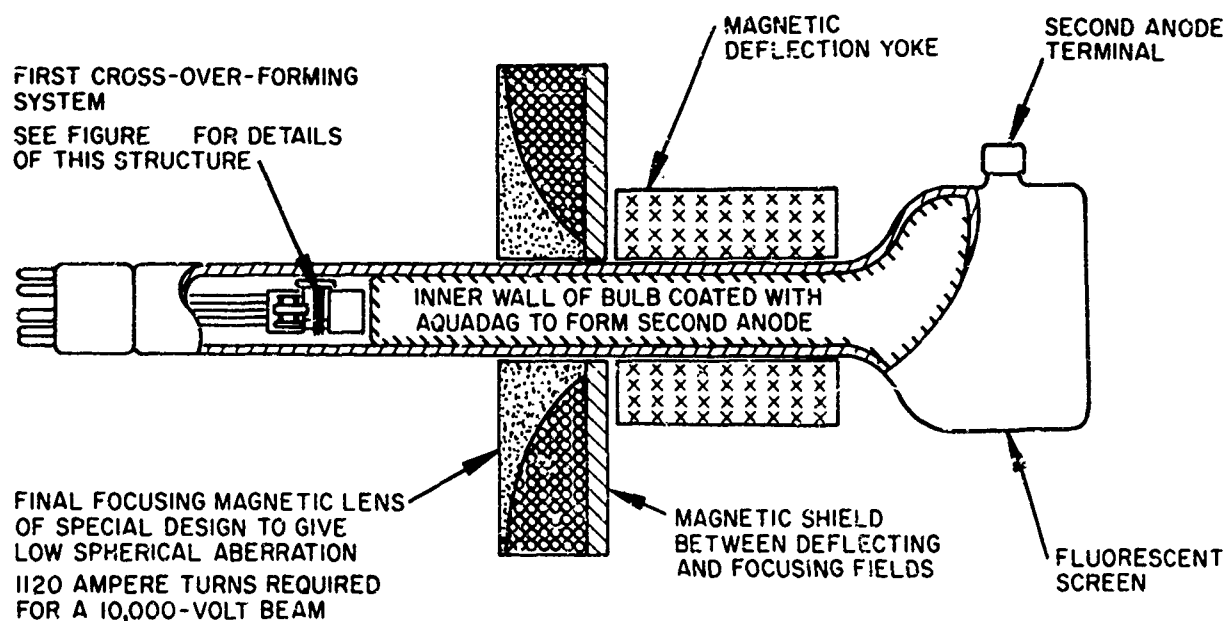


Figure 56. General Assembly of a Developmental Projection Kinescope

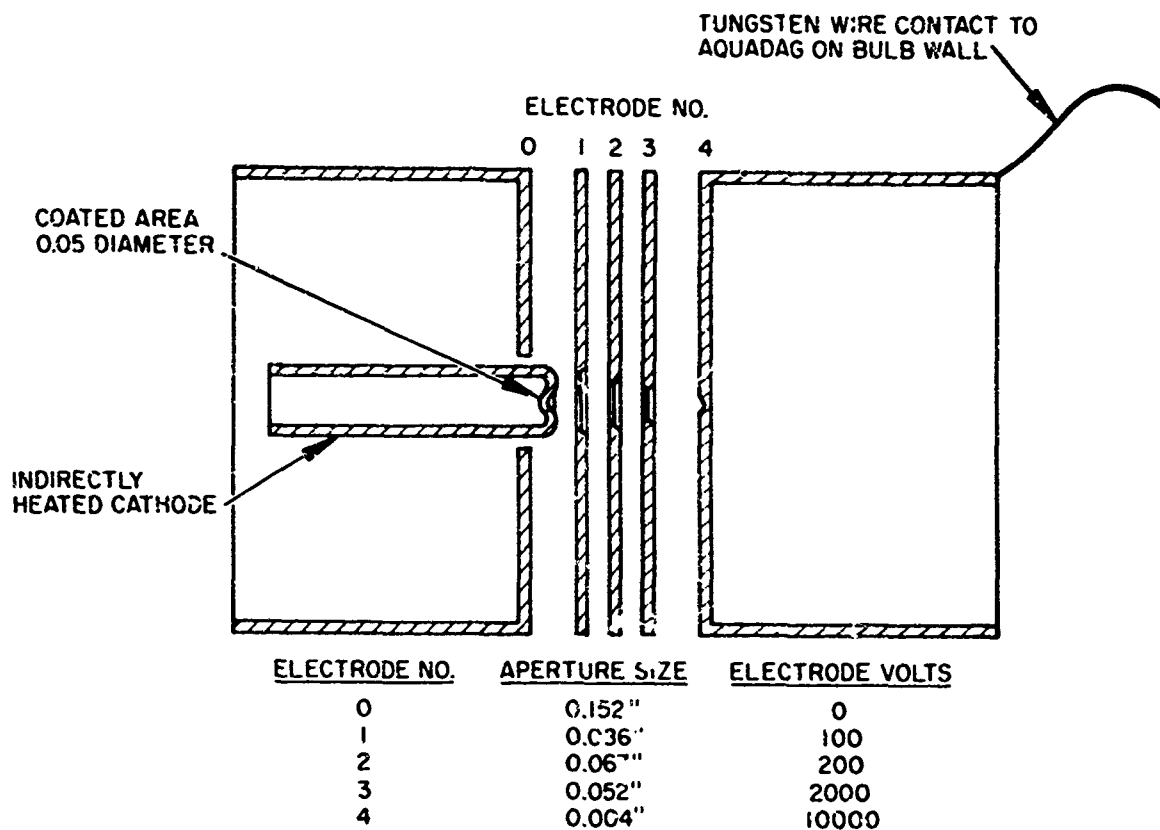


Figure 57. Details of the Electron Gun

The viewing screen in this tube was 4 inches in diameter. In the present instance we require an 8-inch diameter viewing screen and a spot diameter of 0.008 inches. If we redesign the structure as shown in Figure 58 below leaving the object distance unchanged but change the image distance from 160 mm to 280 mm and make allowance for the fact that the voltage has been increased 3-fold and the current density has been increased 20-fold the numerical values to be inserted in equation (2) will now be

$$d = \text{limiting aperture diameter} = 0.0017 \text{ in.} = 4.3 \times 10^{-3} \text{ cm}$$

$$j_0 = \text{current density at the cathode} = 2.0 \text{ amp/cm}^2$$

$$E = 30,000 \text{ volts}$$

$$\frac{e}{KT} = 11.6$$

$$\sin^2\left(\frac{\theta}{2}\right) = \sin^2(3^\circ) = 2.7 \times 10^{-3}$$

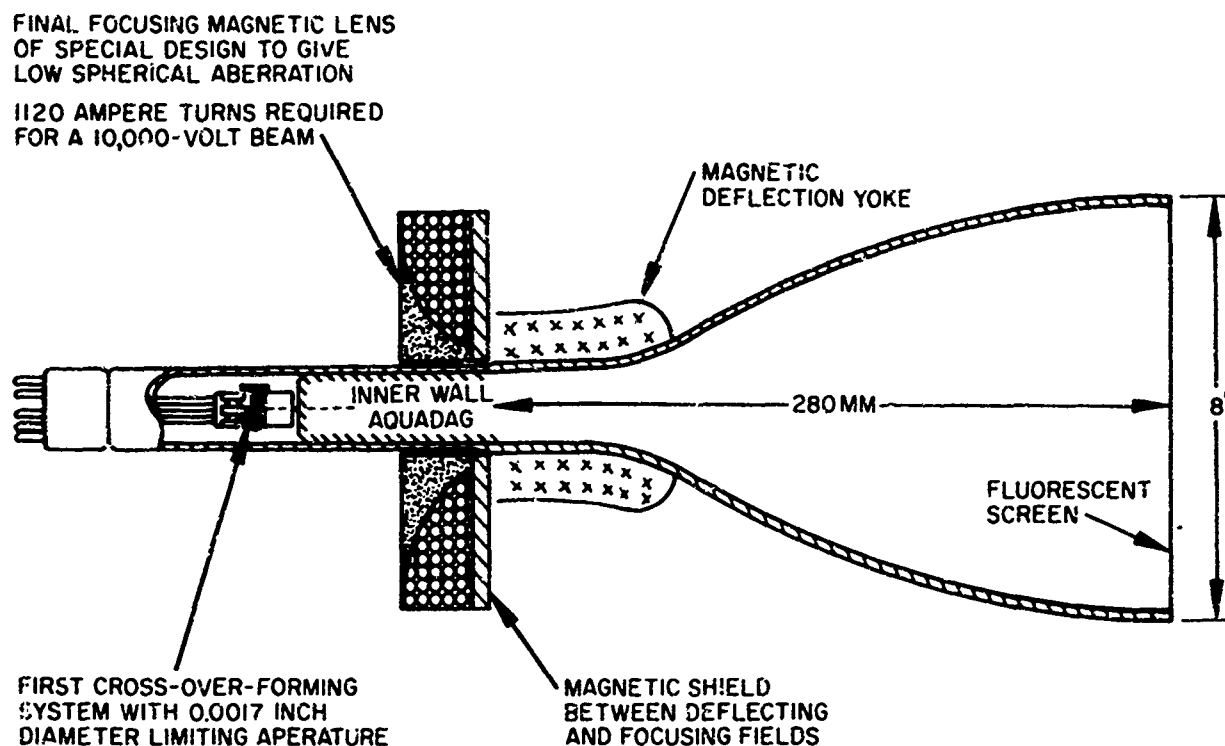


Figure 58. Redesigned Kinescope

This indicates that a beam current of

$$I_b = 0.6 (4.3 \times 10^{-3})^2 (2.0) (11.6) (3 \times 10^4) (2.7 \times 10^{-3}) = 21 \text{ ma}$$

should be possible.

The proposed deflection angle

$$\tan^{-1} \frac{(4)(25.4)}{280} \approx 20^\circ$$

exceeds that employed in the original instance, but the state-of-the-art in wide angle deflection systems has improved greatly since then. By adding dynamic focus and dynamic correction of astigmatism (Schlesinger Wagner, 1965, pp. 478-484) it should be entirely practical to work at this deflection angle.

With a beam current of 21 ma at a voltage of 30 kv we would have a phosphor power input of 630 watts. This may exceed the power handling capability of the phosphor. Theater projection CRT's such as the 7NP4

(Zworykin, 1954, pp. 437-440) operate at beam currents of 4 ma with anode voltages of 75 kv. This corresponds to peak power inputs of 375 watts. The problem is obviously more difficult at high resolution but the practical operating level will no doubt be in the range of 500 watts. It is interesting to observe that the phosphor efficiency can be relatively low under these conditions. If we assume 600 lumens/watt and only 6 percent efficient phosphor we obtain a brightness of

$$\text{Brightness} = \frac{(0.05)(500)(600)(144)}{(5.7)^2 \pi} = 22,000 \text{ foot lamberts}$$

In the 7NP4 theater projection CRT highlight brightnesses of 20,000 foot lamberts are obtained at efficiencies up to 7 percent so this would seem to be a reasonable design.

AREAS REQUIRING FUTURE WORK

The immediately important thing to do is to build a feasibility model of the proposed design high brightness direct view CRT. During the actual construction many engineering compromises will be required. Preliminary experiments must be made to optimize the various factors because there is no existing data to indicate the behavior of many of the materials here involved in the power ranges here contemplated. For example, studies should be made of the permissible phosphor loading. Studies should be made of the permissible loading at the beam defining aperture. Tests should be made of the possible advantages of semi-transparent phosphors. Although transparent phosphors have lower relative efficiencies, they do have greater power handling capability.

In the process of fabricating this feasibility device many new problems will doubtless arise. Operational procedures must be developed so that the beam can be aligned in the aperture before full beam voltage or power is applied to avoid damaging the aperture. The solution of problems like these is well within the state-of-the-art for experts in the field. It would be highly desirable to engage a contractor with broad experience in the several critical areas of high current density cathodes, high current density CRT's and high power dissipation capability phosphors.

For the long term picture materials research is desirable on improved phosphors particularly in the area of semi-transparent phosphors since they have the capability of better resolution and greater power handling capability. In the still longer term picture we must closely watch the progress being made by other devices, particularly lasers. Although the techniques for laser deflection are as yet rudimentary, it seems highly probable that the lasers will one day be the preferred means of generating high brightness displays.

SENSING AND DATA PROCESSING

OVERVIEW

With the view of determining the critical sensing and data processing problems that accompany the use of the candidate pictorial displays, an examination of the allowable error allotment for each of the pictorial displays was conducted where applicable.

The VSD skeletal and contact analog displays are, compared to conventional instrumentation, extremely high gain displays that will not inherently damp signals generated by the sensors. It makes no sense, however, to have such high gain and fast response in the display unless the sensor system can provide accurate, relatively noise free, short time constant intelligence. Based on our knowledge of the threshold read-out capabilities of the pilot when using such displays it is possible to estimate the requirements for some of the more important accuracy and temporal characteristics for each displayed dimension based solely on perceptual rather than operational considerations. The results of such an exercise are provided in Table XIII for the representative case of a display with unit magnification, a symbol line width of 3 mils, and tube with a vertical dimension of 8 inches and a resolution (q) of 1000 lines viewed from 24". The bias error values were based on our knowledge of thresholds for each displayed dimension. The variability figures were based on best guesses. The dead time and time constants were based on thresholds for the perception of casual relations.

The requirements for the HSD map displays were shown in the sketches illustrating those displays. The requirements for the raw sensor displays do not lend themselves to this form of description and therefore have been omitted.

TABLE XIII. ACCURACY REQUIREMENTS FOR VSD INFORMATION

ALLOWABLE ERROR AT DISPLAY										
Symbol	Information	SKELETAL VSD				CONTACT ANALOG VSD				
		Dead Time	Time Constant	Bias Error	Variability $\pm \sigma$	Dead Time	Time Constant	Bias Error	Variability $\pm \sigma$	
θ	Pitch	50 msec.	100 msec.	6 min.	± 12 min.	50 msec.	100 msec.	6 min.	± 12 min.	
ϕ	Roll	50 msec.	100 msec.	6 min.	± 12 min.	50 msec.	100 msec.	6 min.	± 12 min.	
ψ	Heading	50 msec.	100 msec.	6 min.	± 12 min.	50 msec.	100 msec.	6 min.	± 12 min.	
α	Angle of Attack	50 msec.	100 msec.	6 min.	± 12 min.	50 msec.	100 msec.	6 min.	± 12 min.	
V	Velocity Vector	50 msec.	100 msec.	6 min.	± 12 min.	50 msec.	100 msec.	6 min.	± 12 min.	
θ_T	Depression Angle of Touchdown Point	50 msec.	100 msec.	6 min.	± 12 min.	N.A.	N.A.	N.A.	N.A.	
ψ_T	Bearing of Touchdown Point	50 msec.	100 msec.	6 min.	± 12 min.	N.A.	N.A.	N.A.	N.A.	
ψ_R	Heading with Respect to Command (or Runway)	50 msec.	100 msec.	6 min.	± 12 min.	50 msec.	100 msec.	6 min.	± 12 min.	
V_C	Command Velocity Vector	50 msec.	100 msec.	6 min.	± 12 min.	50 msec.	100 msec.	6 min.	± 12 min.	
R	Range to Touchdown (for Carrier Symbol)	100 msec.	200 msec.	2% of Range	$\pm 1.5\%$ of Range	(See Unique Ground Position Below)				
D_V	Vertical Angular Deviation from Nominal "Glide Slope"	?	?	?	?	N.A.	N.A.	N.A.	N.A.	
D_H	Horizontal Angular Deviation from Nominal Centerline	?	?	?	?	N.A.	N.A.	N.A.	N.A.	
θ_f	Command Flight Path Pitch (Contact Analog)	N.A.	N.A.	N.A.	N.A.	100 msec.	100 msec.	12 min.	± 6 min.	
ψ_f	Command Flight Path Heading (Contact Analog)	N.A.	N.A.	N.A.	N.A.	100 msec.	100 msec.	12 min.	± 6 min.	
D_f	Command Flight Path Lateral Position (Contact Analog)	N.A.	N.A.	N.A.	N.A.	100 msec.	200 msec.	2% of Aircraft Error	$\pm 1.5\%$ of Aircraft Error	
H_f	Command Flight Path Altitude (Contact Analog)	N.A.	N.A.	N.A.	N.A.	100 msec.	200 msec.	5% of H_f	$\pm 3\%$ of H_f	
S_{xf}	Command Flight Path Forward Velocity (Contact Analog)	N.A.	N.A.	N.A.	N.A.	100 msec.	200 msec.	3% of S_{xf}	$\pm 3\%$ of S_{xf}	
S_{yf}	Command Flight Path Lateral Velocity (Contact Analog)	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	
	North Velocity Ground (Contact Analog)	N.A.	N.A.	N.A.	N.A.	100 msec.	200 msec.	3% of Velocity	$\pm 3\%$ of Velocity	
	East Velocity Ground (Contact Analog)	N.A.	N.A.	N.A.	N.A.	100 msec.	200 msec.	3% of Velocity	$\pm 3\%$ of Velocity	
	North Position of Unique Ground Position	100 msec.	200 msec.	2% of Range	$\pm 1.5\%$ of Range	100 msec.	200 msec.	2% of Range	$\pm 1.5\%$ of Range	
	East Position of Unique Ground Position	100 msec.	200 msec.	2% of Range	$\pm 1.5\%$ of Range	100 msec.	200 msec.	2% of Range	$\pm 1.5\%$ of Range	
	Altitude of Ground or Carrier Symbol	100 msec.	200 msec.	5% of Altitude	$\pm 3\%$ of Altitude	100 msec.	200 msec.	5% of Altitude	$\pm 3\%$ of Altitude	
	Carrier Heading	100 msec.	200 msec.	0.5°	$\pm 0.25^\circ$	100 msec.	200 msec.	0.5°	$\pm 0.25^\circ$	

1 When Ground Not Tied to Unique Ground Position Symbol.

The values shown in this chart are indicative of the sensor requirements for each display parameter. Although the accuracies required are, in some instances, more stringent than obtained in current operational aircraft, they are by no means beyond the state of the art. Those that, in our judgment, are clearly within the state of the art have been considered non-critical items and little time was spent in further examination of them. The necessary policy has been to narrow down the range of issues studied in order to concentrate the effort on those items that are not currently sensed or those functions that are critical for the system to achieve the required accuracy or response rate. The critical problems have been summarized in Table XIV.

The table shows, for each aircraft type, display type, and mission segment, the parameters or functions that are critical or novel. The cell entries in the chart are necessarily terse so in order to clarify the meaning of each of the cell entries a description of the problem suggested by each cell entry will be made. Cells will be identified by column number and row letter. Some of the critical problems that have been isolated will be discussed in full in a later section of the report.

A-1: Take-off, Fixed Wing, Skeletal VSD.

With few exceptions all of the parameters displayed on the skeletal flight display as illustrated in Figure 20 may be sensed quite adequately by state of the art equipment. Two important exceptions are the aircraft velocity vector and the desired or command velocity vector. It is not difficult to conceive methods for deriving the velocity vector in any system that has an inertial or Doppler navigator already on board. Provided adequate symbol quickening is employed to obviate the misleading transients that occur (as discussed previously), the problem of sensing and displaying the velocity vector does not seem acute. It is mentioned here only because display of this parameter is both novel and important.

The phrase "parameter prediction," occurring in cell A-1 and subsequently, refers in the ideal case to the display of the predicted velocity vector. Prediction of the aircraft velocity vector would take considerable data processing equipment, and it is believed that a reasonable approximation can be achieved by employing turn rate and pitch rate. The "prediction" must be over some reasonable time interval, and the precise nature of the prediction remains to be worked out.

Table XIV. CRITICAL FUNCTIONS WITH IMPLICATIONS
FOR SENSING AND DATA PROCESSING

VERTICAL SITUATION DISPLAY	FIXED WING			STEEP GRADIENT		
	MISSION SEGMENT			MISSION SEGMENT		
	TAKE-OFF AND CLIMB 1	POINT TO POINT NAVIGATION 2	APPROACH AND LANDING 3	TAKE-OFF AND CLIMB 4	POINT TO POINT NAVIGATION 5	APPROACH AND LANDING 6
SKELETAL A	1 VELOCITY VECTOR 2 PARAMETER PREDICTION	1. VELOCITY VECTOR 2 PARAMETER PREDICTION 3 VELOCITY VECTOR COMMAND	1 VELOCITY VECTOR 2 PARAMETER PREDICTION 3 VELOCITY VECTOR COMMAND 4 LANDING SPOT LOCATION	1 VELOCITY VECTOR 2 PARAMETER PREDICTION 3 OBSTACLE AND WIRE AVOIDANCE	SAME AS 2A PLUS OBSTACLE AND WIRE AVOIDANCE	SAME AS 3A PLUS OBSTACLE AND WIRE AVOIDANCE
ANALOG B	1 VELOCITY VECTOR 2 PARAMETER PREDICTION 3 VELOCITY VECTOR COMMAND	SAME AS 2A	SAME AS 3A	SAME AS 4A PLUS VELOCITY VECTOR COMMAND	SAME AS 5A	SAME AS 6A
LITERAL C	N A	FRAME TIME, DYNAMIC RANGE, AND RESOLUTION OF IR & LLTV	SAME AS 2C PLUS CHARACTER- ISTICS OF NON-AUTONOMOUS SYSTEMS ("MICRO-VISION")	LASER VSG FOR WIRE AVOIDANCE	SAME AS 2C, 3C	SAME AS 3C
HORIZONTAL SITUATION DISPLAY	MISSION SEGMENT			MISSION SEGMENT		
	TAKE-OFF AND CLIMB 1	POINT TO POINT NAVIGATION 2	APPROACH AND LANDING 3	TAKE-OFF AND CLIMB 4	POINT TO POINT NAVIGATION 5	APPROACH AND LANDING 6
SKELETAL X	N.A.	N A	N A	N A	N.A.	N.A.
MAPS, CHARTS AND REFERENCE MATERIALS Y	1 INITIAL POSITION	1 POSITION UPDATE 2 FUEL-RANGE MEASUREMENT & COMPUTATION 3 VELOCITY VECTOR COMMAND	1 POSITION UPDATE 2 LANDING SPOT LOCATION & HEADING 3 VELOCITY VECTOR COMMAND	1. INITIAL POSITION	1 POSITION UPDATE 2 FUEL-RANGE MEASUREMENT & COMPUTATION 3 VELOCITY VECTOR COMMAND	1. POSITION UPDATE 2. LANDING SPOT LOCATION & WIND 3. VELOCITY VECTOR COMMAND
PATTERN SENSOR DISPLAYS Z	N.A.	THE USE OF RADAR, IR, & LASER DEVICES FOR OBJECT RECOGNITION	SAME AS 2Z	N A	SAME AS 2Z	SAME AS 2Z

DISPLAY FUNCTIONS OR PARAMETERS THAT ARE CRITICAL OR NOVEL
IN TERMS OF SENSOR AND DATA PROCESSING REQUIREMENTS FOR TWO
VEHICLE TYPES AND THREE MISSION SEGMENTS

The representation of the command velocity vector can probably be omitted from the display during take-off. It has been assumed throughout the study that fixed wing aircraft are carrier launched and that in such launching, the initial phases of climbout may be achieved satisfactorily by pitch rotation.

A-2: Navigation, Fixed Wing, Skeletal VSD.

Here again the parameters displayed are not unusual and are similar to those discussed in the previous paragraphs. Added to the display is a command symbol representing the optimum velocity vector. As it is intended that the pilot control the velocity vector, an index of desired as well as current performance is desirable. When an end goal is in sight on the display (the landing strip) a command velocity vector may not be required. When the end goal is not in sight or when for other reasons the aircraft should fly within certain constraints, then it is required that the display present not only the end goal but the path to the goal, i. e., the command velocity vector. In the vertical plane the achievement of this desired vector constitutes a longitudinal control program for the aircraft, and the primary considerations in the phases of flight we are considering are time, fuel consumption, and kinematic limits. If the symbol representing the command is to move in both az and el, the calculation of the optimum and the conversion of this to an az-el steering signal for the pilot must be carried out. The optimization of the trajectory in the vertical plane is the prerequisite for defining the command velocity vector in that plane.

Generation of the optimum velocity vector in the horizontal plane is nothing more than the familiar navigation problem of calculating the appropriate track, taking due regard for weather, terrain, enemy defenses, and the like, and it is difficult to conceive of analytic ways of determining the optimum horizontal velocity vector. Course programs established during briefing can be stored visibly on the map and, if necessary, converted to a steering command for the pilot. If, while the aircraft is on an individual sortie, changes in the planned course are to be made after take-off on the grounds of information derived from autonomous sensors, then such changes most likely will be carried out by extensive use of the HSD display which would be used to display the newly assimilated data.

In conjunction with other equipment, the HSD could be used as a basis for generating lateral steering commands for the pilot. In addition to the fact that the solution to this problem does not lend itself to formal analysis, the issue is basically not one of sensing or data processing but one of working out logical procedures for the aircrew to use in exploiting the HSD, an on-board computer, autonomous sensors, and other associated equipment. As exploitative procedures must be worked out individually for each unique system, it was decided that attempts to derive an optimum lateral velocity vector should be dropped and that the emphasis should be placed on the more generic problem of optimizing the velocity vector in the vertical plane.

A-3: Landing, Fixed Wing, Skeletal VSD.

The additional information required on the display for the landing phase is the location and heading of the carrier. How to sense this in general terms is not difficult to conceive, but how to achieve the required accuracy and reliability if one assumes the necessity of landing without the pilot ever establishing visual contact is not readily apparent. There are also secondary display problems that have to do with drawing the carrier with the correct perspective and in a scale suitable to the resolution limits of the display tube. The problem of locating the landing spot is generic, being required for all landing displays, and is therefore one that is considered critical.

A-4: Take-off, Steep Gradient, Skeletal VSD.

The takeoff display requirements for steep gradient vehicles are similar to those of other aircraft with the exception that because of their flight characteristics and their normal operational milieu, obstacles such as trees and wires assume greater importance. To avoid such lethal objects the pilot must be informed of both their presence and position. Logical places to present such information are on the windscreen during contact flight or on the VSD during instrument flight. Because the space in which the vehicle operates is described in feet rather than miles, the sensor problem for helicopters is compounded by the requirement for measurement at extremely short ranges.

A-5: Navigation, Steep Gradient, Skeletal VSD.

No unique problems.

A-6: Landing, Steep Gradient, Skeletal VSD.

The problems of approach and landing for steep gradient vehicles are similar to those already discussed with the exception that the landing spot must be located with extreme accuracy, and this spot may be a simple clearing rather than the carrier. How to do this with both autonomous and non-autonomous sensors are major issues.

B-1 through B-6: All Phases, All Aircraft, Contact Analog.

With the exception of North, East, and vertical velocities the analog display for these mission segments requires no more sensed information than the skeletal; the only difference is the form of encoding the data. The change that represents the most marked departure from the skeletal display is to encode the command velocity vector as the so-called "flight path". It takes ten dimensions to specify the plane of the ribbon for each straight segment, and if the ribbon is to be painted correctly as a so-called "highway-in-the-sky" then this data must be supplied for each such segment. If a curved ribbon is desired the problem is even more complex. The generation of the optimum velocity vector as a command ribbon is not so much a problem of sensing as of data processing.

C-1: Take-off, Fixed Wing, Literal VSD.

Not applicable.

C-2: Navigation, Fixed Wing, Literal VSD.

The major issue in the use of az-el literal displays on the VSD during navigation has to do with the frame time, dynamic range, and resolution of possible sensors: LLTV and IR. It is envisioned that either of these techniques could conceivably be used at night in order to identify checkpoints and thereby aid in establishing a fix. For high-speed fixed-wing aircraft, this application has a promising potential.

C-3: Landing, Fixed Wing, Literal VSD.

The use of literal sensors for landing was discussed in previous sections, and it was pointed out that such use depended on the attainment of certain characteristics of the sensor display system. It should also be mentioned that raw data sensed by LLTV or IR could be mixed on the display with symbolic information, for example, by mixing the skeletal display in registry with the LLTV output.

C-4 through C-6: All Phases, Steep Gradient, Literal VSD.

Nothing unique.

X-1 through X-6:

Not applicable. Skeletal Horizontal Situation Displays are already developed and in operational use as standard instruments.

Y-1 through Y-6: All Phases, All Aircraft, Analog HSD. (Maps and Reference Materials)

In the map displays the basic sensing and data processing problem is to position ownship and other symbols correctly. A second problem is accurate positioning of the fuel-range circle which depends on fuel measurement as well as standard navigational computations.

Z-1 through Z-6: All Phases, All Aircraft, Literal HSD. (Sensor Displays)

With inertial or doppler sensors, integration errors result in accumulated position errors that would lead to serious consequences in those instances where the aircraft operates close to the ground. Such errors may be corrected by position updating the navigation system using identifiable checkpoints whose positions are known. This would normally be done in conjunction with the display of raw data. As the primary use of the raw display is to allow the operator to identify the checkpoint, the major problem is to be able to stipulate the conditions under which the operator could recognize the target where the term target is used in the broad sense to mean any physical object.

The operator's ability to classify and name targets is directly related to the characteristics of the pattern sensor. As was suggested previously, once such a recognition is made, the way is open to use the imagery directly as in the example of landing the helicopter in the clearing or indirectly to update the navigation system. The information gleaned from these pattern sensors or other sensors may also be used to supplement information appearing on the map display by superposing raw with stored data and thus allow the display of current information important in a rapidly changing tactical situation.

Summary

From this discussion a list of crucial sensing and data processing problems that have been analyzed may be drawn up. This list is not exhaustive but contains only those critical items that will be discussed in following sections of this report.

- 1) Sensors that permit the recognition of significant objects through the media of displays are required for some mission segments. The output of such sensors would be used by the crew to:
 - a) update the navigation system
 - b) add current data to map display for tactical use.
- 2) Sensors that detect obstacles during helicopter or VTOL takeoff, landing, and low altitude navigation.
- 3) The problem of sensing or calculating the velocity vector. This is a requirement for all the flight displays.
- 4) The calculation or derivation of the command velocity vector in both the vertical and horizontal plane as well as means for converting the information to a signal appropriate for moving the display symbol. Calculation in the vertical plane is a requirement for all flight displays. The horizontal optimum will be largely dependent on locally sensed threats and therefore may be determined by the aircrew.

Each of these problems will be discussed, in turn, in the following section.

NAVIGATION UPDATING

One of the major uses of the HSD display is to employ it for the presentation of pattern sensor information in order that the crew may acquire and designate targets, checkpoints, and landmarks. The general conditions that would enable the crew to identify "targets" were discussed in an earlier section of this report. In this section the particular case of utilizing pattern sensors to update the navigation or fire control system will be further analyzed with the view of determining sensor requirements.

When the information from such sensors is displayed, the display may be used for updating by having the crew designate checkpoints whose geographic coordinates are known. This implies that the possible checkpoint position error is considerably smaller than the accumulated navigation error. Even if the desired checkpoint is part of a larger complex there are many regions of the earth where the natural geography or the political development is such that there is a dearth of large unique objects or patterns that would form such a useful complex. This means that small checkpoints must be used — these may be small lakes, clusters of buildings, terrain features, or other identifiable features. If these features are small with respect to sensor resolution, then they would not be usable as checkpoints. However, with relatively high resolution sensors such as coherent on receive doppler systems (CORDS) and high resolution forward looking infrared sensors (FLIR), some of these features become identifiable and hence usable as checkpoints.

System Requirements

In order to determine the sensor requirements for position updating using small checkpoints, we are proceeding with an assumption of navigation subsystem accuracy derived from manufacturers' specifications. With this parameter set, required fields of view, resolution, contrast, resolving capabilities and rough costs of various advanced sensors — low light level television, forward looking infrared, and high resolution radar — must be traded-off to determine subsystem requirements. Such a trade-off study is included here. Table XV defines the symbols used.

Table XV

Symbol	Description	Units
S	Azimuth	Feet
R	Range	Feet
σ_N	Navigation System Accuracy (1 sigma) at the time of fix taking	Feet
K_1, K_2, K_3	Constants	$^{\circ}\text{C radians sec}^{1/2}(K_2)$
h	Altitude	Feet
ΔT_n	Temperature Sensitivity	$^{\circ}\text{C}$
δ	Angular resolution	Radians
η_s	Scan efficiency	
n	Number of detectors	
Ω	Solid angle field of view	Steradians
θ	Azimuth field of view	Radians
ϕ	Elevation field of view	Radians
t	Scan time	Seconds

1. $S = 2R \sin \frac{\theta}{2}$

2. $R = K_1 h$

From previous experience $10 < K_1 < 20$

2a. $R \cong 15h$
combining 1 and 2a

3. $30h \sin \frac{\theta}{2} = S$

For a 95 percent chance (2σ) of having a checkpoint within the field of view

$$4. \quad S = 4 \sigma_N$$

Combining 3 and 4

$$5. \quad 7.5h \sin \frac{\theta}{2} = \sigma_N \quad \text{From IR sensor considerations}$$

$$6. \quad \frac{\Delta T_n S^2 (\eta_{snt})^{1/2}}{\Omega^{1/2}} = K_2$$

$$7. \quad \Omega \cong \theta \cdot \emptyset$$

$$8. \quad q = K_3 \emptyset$$

For reasonable coverage in the along track path

$$8a. \quad q = 3\emptyset$$

Combining 6 and 8a

$$9. \quad \frac{\sqrt{3} \Delta T_n \delta^2 (\eta_{snt})^{1/2}}{\theta} = K_2$$

Using state of the art parameters, i. e., $\Delta T_n = 0.5^\circ\text{C}$, $\delta = 1 \text{ mrad}$,

$\eta_s = 0.8$, $n = 36$, $t = 2.5 \text{ sec}$, and $\theta = 30^\circ$, K_2 can be found.

$$10. \quad k_2 = 14 \times 10^{-6}$$

Using this value and combining 5 and 9

$$11. \quad \sigma_N = 7.5h \sin 0.62 \times 10^5 \Delta T_n \delta^2 (\eta_{snt})^{1/2}$$

For ΔT_n , σ , η_s , n , and t fixed at 0.5°C , 1 mr , 0.8 , 36 , and 2.5 sec ,

respectively. Figure 59 shows one sigma navigation accuracy required (σ_N) as a function of altitude h .

For h , δ , η_s , n , and t fixed at 500 , 1 mr , 0.8 , 36 , and 2.5 sec , respectively,

Figure 60 shows σ_N as a function of ΔT_n .

For h , ΔT_n , η_s , n , and t fixed at 500 , 0.5°C , 0.8 , 36 , and 2.5 sec ,

respectively, Figure 61 shows σ_N as a function of δ

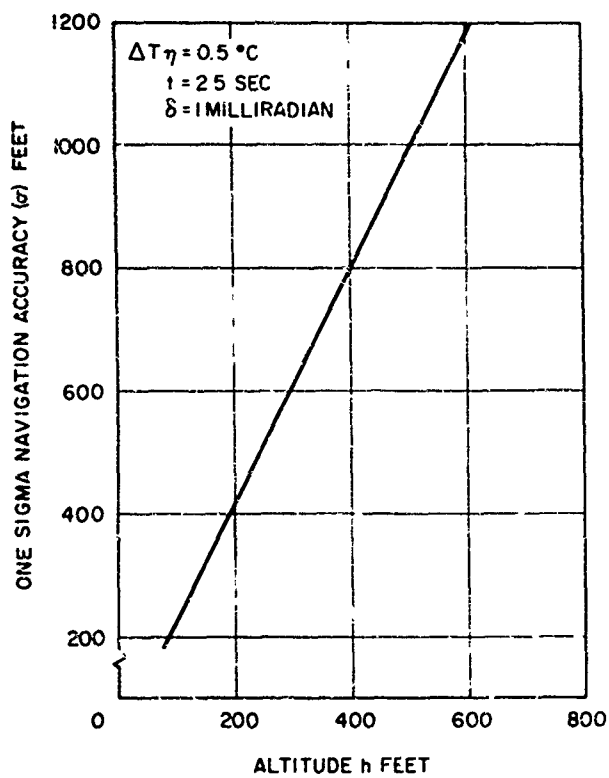


Figure 59

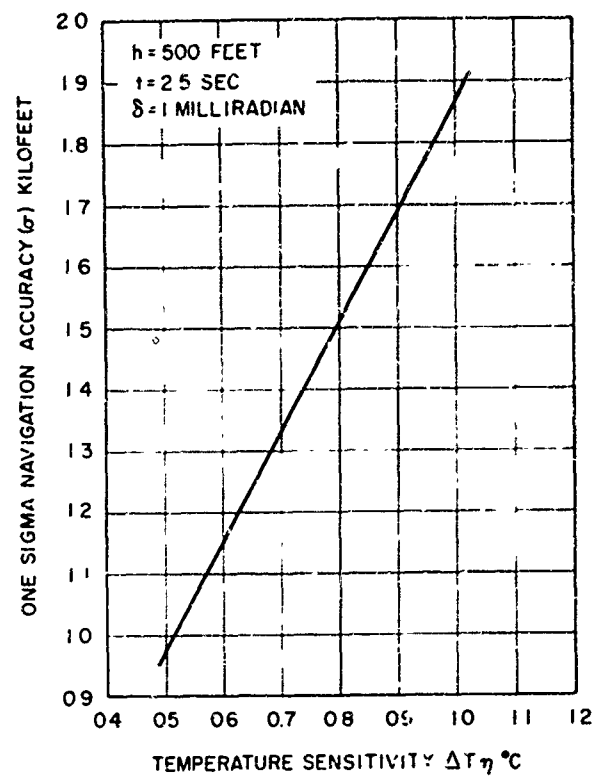


Figure 60

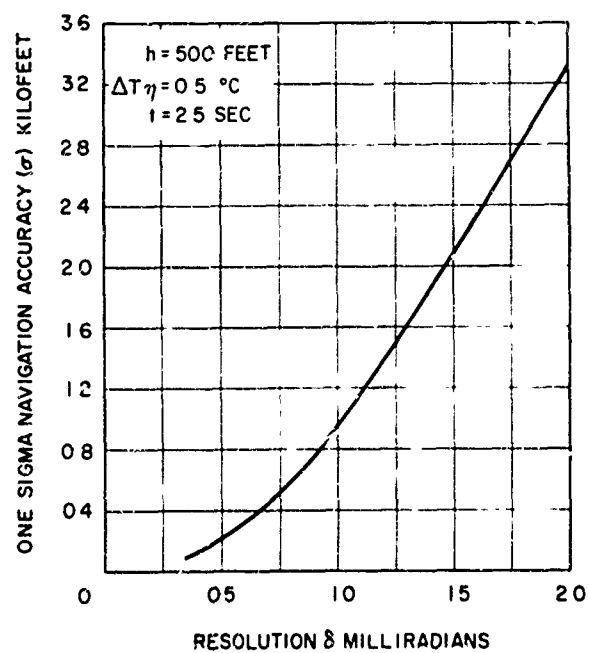


Figure 61

Navigation Accuracy As A Function of Three Variables

When the best checkpoints are also the most heavily defended, it is desirable not to overfly the checkpoint for updating purposes. This desired offset technique could be implemented with a laser used in conjunction with IR or TV and appropriate coordinate transformation in a navigation computer. This is known as offset navigation updating.

Offset navigation updating can be most important as a compromise technique enabling both navigation accuracy and enhanced survival probabilities. If the checkpoint is well defended it may be absolutely mandatory to employ this technique.

Many problems are raised by the consideration of this technique. Firstly, it becomes desirable to have real time checkpoint recognition. However, for reasonable offsets and realistic checkpoints this is often impossible. A solution to this is available by taking a radar "snapshot" of the area in which the checkpoint is expected to be and examining the resulting display later.

The snapshot technique requires a number of equipments to solve problems which arise from its use. For instance, a means of keeping track of time and aircraft velocity since the time of taking the snapshot is needed. In addition, a method of extracting radar range to the checkpoint after many seconds or even minutes have elapsed because of display search and recognition time, is also needed.

An operational sequence which would be employed is indicated here by steps.

- 1) Point sensor in accordance with the expected location of the checkpoint.
- 2) Pop up.
- 3) Generate a "snapshot" of the area with the expected coordinates of the checkpoint as the center.
- 4) Return to a safe altitude.
- 5) Study the "snapshot" - identify the checkpoint.
- 6) Place cursors over the identified checkpoint.
- 7) Enter the updated position in the navigation computer.

The specific equipments needed to implement this technique are:

- 1) A high resolution sensor
- 2) A navigation system
- 3) Servo drives on the sensors
- 4) An accurate clock
- 5) A means of ranging
- 6) A velocity sensor
- 7) A computer

Various parameters associated with the required equipments must be set so that the checkpoints can be recognized and updating accomplished accurately. These parameters are:

- 1) Sensor resolution
- 2) Sensor field of view
- 3) Sensor positioning accuracy
- 4) Navigation system position accuracy
- 5) Velocity sensor accuracy
- 6) Ranging accuracy
- 7) Clock accuracy
- 8) Computer accuracy
- 9) Display dimensions
- 10) Display resolution

Recognizing small checkpoints can be a difficult task. A formula based on work done by H. H. Bailey of the RAND Corporation expressing the quality of visual imagery needed for recognition has been used (Bailey, 1960). A change in one term should allow its use with radar imagery.

$$P_R = \left[1 - e^{-\frac{c}{0.15}} \right] \left[1 - e^{-\frac{N}{5}} \right] \left[1 - e^{-\frac{B-3'}{7.5'}} \right] \left[1 - e^{-\frac{10 \text{Tr} A_T}{A_D K}} \right]$$

c = contrast

N = number of resolution elements subtended by the checkpoint

B = ϕ subtended by checkpoint on the display

A_T = target area

A_D = area field of view on display

T_r = search time of display area

K = fraction of display area that is of interest

By assuming a display size and permitting a long search time, A_T may be computed if an overall value of the last bracket is set. For an overall value of P_R = 0.95 the last bracket should equal about 0.98. Thus, for an eight-inch diameter tube and a search time of 60 seconds

$$0.98 = 1 - e^{-\frac{10 \times 60 A_T}{\frac{\pi 64}{4}}}$$

$$A_T = 0.327 \text{ in}^2 \text{ satisfies this condition}$$

This means that a checkpoint linear dimension of about 0.57 inches should be displayed. If the entire display represents a linear ground dimension of two nautical miles, then the checkpoint ground dimensions must be about 850 feet by 850 feet. This is a pessimistic value since the value of K was assumed to be unity. Actually the availability of charts, maps, radar imagery, photographs or other aids should permit localization of the display search to an octant. This in turn will decrease the required area of the checkpoint by a factor of eight and thus a 300-foot by 300-foot checkpoint will suffice.

The above value scaled to the display dimensions and an assumed viewing distance permits evaluation of the penultimate term. Thus $(1 - e^{-\frac{B \cdot 3'}{7.5'}}) \approx 0.991$ for a viewing distance of 18 inches and a 0.2 inch checkpoint display dimension. The value for a 0.327 inch display dimension is essentially unity.

The display and sensor resolution determine the value of the second term; a 500-line display and a sensor resolution of 25 feet places 12 linear resolution elements on a 300-foot checkpoint dimension. This leads to a value of 0.91 for the second term. Overall probability of detection versus sensor resolution is shown in Figure 62.

The first term contains a contrast factor which is applicable to visual situations. In the radar case it should be replaced by a signal to clutter ratio term. We can assume that the characteristics of the checkpoint and the radar design leads to a value of unity for this term. The overall probability of recognition then becomes (for a 300-foot by 300-foot checkpoint).

$$P_R = 1 \times 0.91 \times 0.99 \times 0.98 = 0.884$$

For a 600-foot by 600-foot checkpoint the recognition probability goes to 99 percent. Figure 63 shows a plot of probability of detection versus checkpoint dimensions. It will be noted that if the curve shown in this Figure is converted to definition vs. P_R , then the curve falls in the region called Level I recognition illustrated on Figure 36. There is excellent agreement between the requirements based on Bailey's equation and those derived from empirical data.

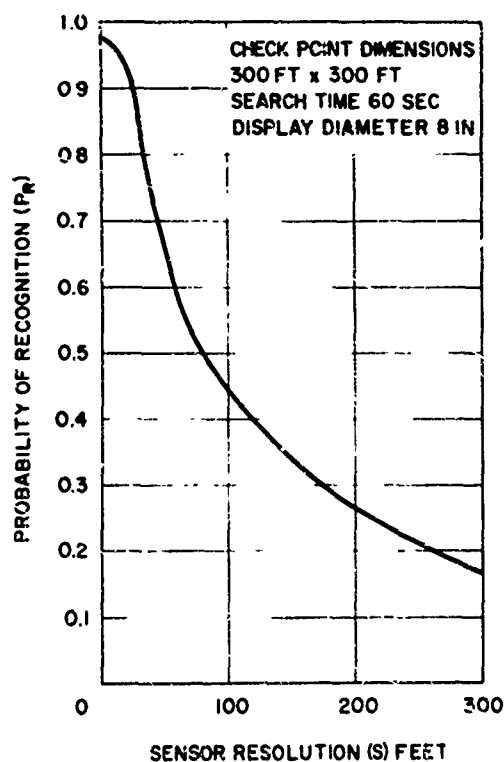


Figure 62. Detection versus Sensor Resolution

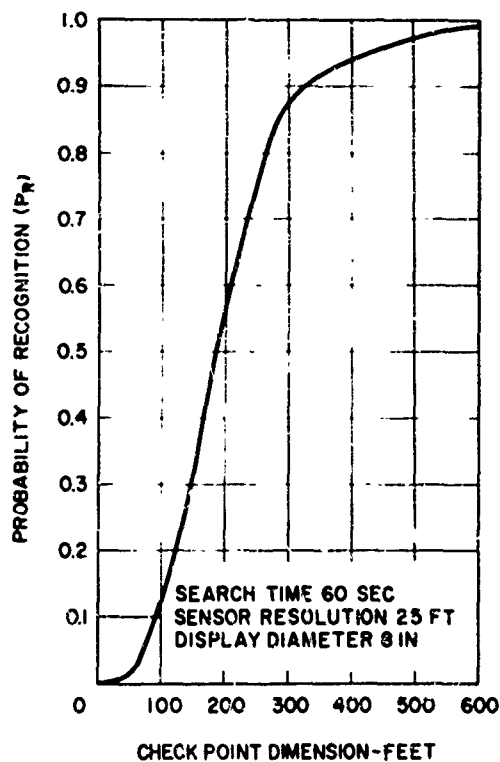


Figure 63. Detection versus Checkpoint Dimensions

System Accuracy

We can now consider the accuracy of the updating procedure. An analysis yields the results shown in Table XVI.

Table XVI. NAVIGATION UPDATING ERRORS

Source	Factor	Errors	
		X	Y
Display nonlinearities	1% of distance from center	30 ft	30 ft
Registration	1/32 in.	47 ft	47 ft
Map Accuracy	1/30-in. X scale	139 ft	139 ft
Inaccurate timing	$V\Delta t = 1000 \times 0.04$	40 ft	0 ft
Inaccurate velocity	$T\Delta V = 60 \times 3$	180 ft	180 ft
Computer round off	Computer complexity versus error	~0 ft	~0 ft
Heading Error	$VT\Delta H \cong 1000 \times 60 \times \frac{1}{1800}$	0 ft	35 ft
Sensor Inaccuracies	$\Delta R = 100$ ft		
	$\Delta\theta = 1$ mrad	112 ft	4 ft
	$\Delta\phi = 1$ mrad		
Altitude error coupled with checkpoint off center on display	$\Delta h = 2$ ft	5 ft	0 ft
Total		269 ft	236 ft

This corresponds to a CEP of about 307 feet.

An explanation of each of the error contributing terms is given below.

Display Nonlinearities

If we assume that the video circuits are used to generate the cursors which are used to pinpoint the location of the checkpoints, the nonlinear error can be confined to the transfer between cursor positioning knobs and the input voltages to the video circuits. If this error source is trimmed to be zero at the display center, then zero error will result when the checkpoint is

precisely centered on the display. However, for a one sigma error of 1/2 nautical mile at updating, a display of two naut. mi. diameter of ground area and a one percent nonlinear error, the updating error is 30 feet in each axis.

Registration

This error stems from human inability to locate centers or other critical points of areas and position cursors over such centers or critical points. Human factors studies have indicated that a value of 1/32 inch is representative of the error resulting from a combination of these effects. This represents a value of 47 feet in each axis for the displayed area.

Map Accuracy

For maps drawn to 1:50,000 scale the accuracy of a point is 1/30 inch X scale.

Inaccurate Timing

Keeping track of the time between information gathering and checkpoint registration is subject to an error which could be as small as 50 microseconds. However, due to priorities within the computer, the error is more likely to be about 0.04 seconds. Thus, the along-track error is the velocity times the time error or 40 feet for a 1000 ft/sec velocity.

Inaccurate Velocity

The time required to detect, recognize, and identify the checkpoint multiplies the velocity errors in each channel and thus contributes to the position error. It is important to note that since updating does not affect the internal navigation loop the velocity error remains undiminished after a position correction. To insure a high probability of identification we have chosen a search time of 60 seconds. This value times a per channel velocity error of 3 feet/second results in an error of 180 feet per channel.

Computer Round Off

This is a cost-accuracy trade-off problem. If, for other purposes, the computer has large storage capacity which can be used for a navigation updating function every 20-30 minutes the error can be negligibly small.

Heading Error

This error actually exists at all times. When considered as part of the overall updating error, it contributes a cross track error equal to the range covered multiplied by the heading error. The range covered between the taking of the "snapshot" and the checkpoint identification is the aircraft velocity (V) multiplied by time (T). Thus, this error is $VT\Delta H$ where ΔH is the heading error. Using values of $V = 1000$ ft/sec, $T = 60$ seconds, and $\Delta H = 2$ minutes - a manufacturer's specification, the error is 35 feet.

Sensor Inaccuracies

There are two inaccuracies associated with the sensor which contribute to the fix taking error. Referring to Figure 64 it is seen that:

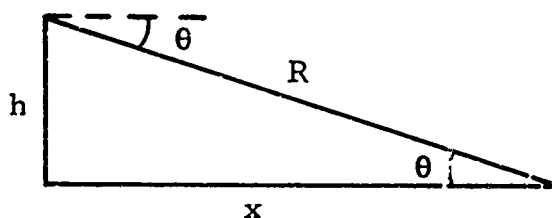


Figure 64. Error Analysis Geometry

$$X = R \cos \theta$$

$$h = R \sin \theta$$

$$\frac{\partial x}{\partial R} = \cos \theta$$

$$\frac{\partial x}{\partial \theta} = -R \sin \theta$$

$$\frac{\partial h}{\partial R} = \sin \theta$$

$$\frac{\partial h}{\partial \theta} = R \cos \theta$$

For no change in altitude at the moment of fixing:

$$\frac{\partial h}{\partial R} \Delta R = -\frac{\partial h}{\partial \theta} \Delta \theta$$

Substituting the above expressions and using

$$E_x = \frac{\partial x}{\partial R} \Delta R + \frac{\partial x}{\partial \theta} \Delta \theta$$

one obtains

$$E_x = -\frac{R \Delta \theta}{\sin \theta}$$

The cross track error is simply

$$E_y = R \cos \Phi \Delta \Phi$$

Using values of

$$R = 5000 \text{ feet}$$

$$\theta = 5.74 \text{ degrees}$$

$$\Phi = 45 \text{ degrees}$$

$$\Delta \theta = \Delta \Phi = 1 \text{ milliradian}$$

$$\Delta R = 100 \text{ feet}$$

one obtains

$$E_x = 112 \text{ feet}$$

$$E_y = 4 \text{ feet}$$

Altitude Error Coupled with Noncentered Checkpoint on the Display

This error exists because an altitude error creates a picture whose dimensions are other than those expected. Reference to Figure 65 shows:

$$\frac{\sin (\theta - \frac{\psi}{2})}{R} = \frac{\sin \frac{\psi}{2}}{X'}$$

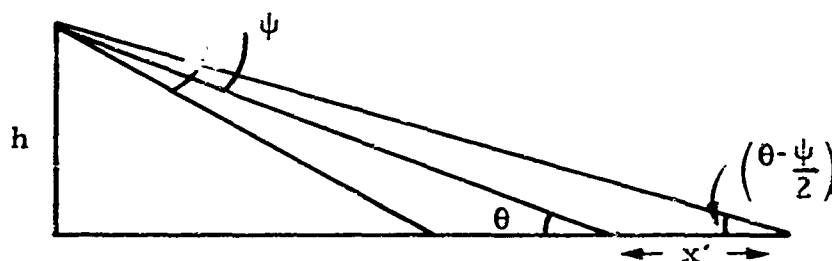


Figure 65. Geometry for Error Due to Alt. Error

For $\frac{\psi}{2}$ small

$$X' \approx \frac{R \frac{\psi}{2}}{\sin \theta - \frac{\psi}{2} \cos \theta} = \frac{\frac{h\psi}{2}}{\sin^2 \theta - \frac{\psi}{2} \cos \theta \sin \theta}$$

When the checkpoint falls half way between the center and the edge of the display (a one-sigma case) the checkpoint to display center dimension is $\frac{X'}{2}$. Evaluating the above expression at $\theta = 4^\circ$, $\frac{\psi}{2} = 1^\circ$, and using the $\frac{X'}{2}$ value one finds the error is $2.34 \Delta h$. For a fine radar altimeter $\Delta h = 2$ feet and the error becomes 4.7 feet. The cross track error is negligible.

Equipment Penalties

The equipment needed to perform offset fixing is listed in Table XVII, along with estimated weights, volumes, power drains, and costs. This data should permit tradeoff analyses to be conducted when the military value of enhanced mission success can be meaningfully inserted.

Table XVII. EQUIPMENT PENALTIES

Equipment	Weight	Volume	Power Req.	Cost	Remarks
Side looking or side squinted radar	280 lbs	4.0 ft ³	1.8 KW	130 K	Possibly needed for targeting
Servo Drives	15 lbs	0.4 ft ³	200 watts	20 K	Needed on radar
Inertial Platform	50 lbs	1.5 ft ³	150 watts	75 K	Some navigational sensor needed always
Computer	12 lbs	0.2 ft ³	50 watts	25 K	Some smaller capacity computer needed always
Display	?	?	?		Needed for other functions

Alternate Sensors

There are other pattern sensing techniques employing pictorial displays which can be used for position updating. Among them are:

IR Fixing

TV Fixing

The following paragraphs describe operational techniques which can be employed to update the navigation system using either of the methods mentioned above.

IR Fixing

This mode is different than the radar snapshot mode. The main reason for this is the low frame rate of the IR sensor. This, together with the necessity of scanning to achieve good resolution creates a problem. The scanning pattern coupled with the aircraft motion generates a distorted image. This can be corrected somewhat but only at the expense of field of view or resolution.

This small field of view greatly limits any IR snapshot mode. However, there is another possibility -- using the IR with a slow frame rate and tracking the area to minimize picture distortion. Even with this precaution, however, changing aspect angles make recognition quite difficult. The primary use of this sensor is real time small target detection and can be considered as a navigation updating aid only because it may be present for its primary purpose.

TV Fixing

A low light television sensor can be used in two ways to enhance checkpoint recognition. Both real time and snapshot modes can be accommodated. In the former case, the sensor is fixed with respect to the airframe and the coverage is generated by the aircraft's motion. The ground coverage is a function of the sensor field of view, elevation angle, and slant range. For the elevation field of view equal to the elevation angle, the ground coverage is about $4/3$ times the slant range. For a slant range of 10,000 feet and a vehicle velocity of 1000 ft/sec, this leaves about 13 seconds for recognition. This requires large or otherwise prominent checkpoints. When a checkpoint is detected, the sensor can be made to track the checkpoint to allow more time for recognition and identification.

In the snapshot TV mode, the sensor is pointed at the checkpoint area with the center at the expected position of the checkpoint. The scene is displayed and "frozen" for as long as required. The operation is then very similar to the radar fixing case.

In both the IR and TV cases the range to the checkpoint is not known. For accurate updating a laser range finder can be used to determine aircraft to checkpoint range in those cases where recognition takes place in real time. In the nonreal time case, the range to the center of the scene at the time of the sensor generation of the display can be measured. When the checkpoint is subsequently found, a correction can be made to account for an off-center image.

OBSTACLE AND WIRE DETECTION

Because helicopters are relatively slow and vulnerable, flight at extremely low altitudes or use of nap-of-the-earth tactics become necessary to ensure survival. At these low altitudes obstacles such as trees, towers, bridges, and suspended wires or ropes become significant flight hazards. As was stated in previous sections many obstacles, particularly wires and cables, are difficult to detect even under the best visual conditions. Thus, sensors capable of detecting these obstacles are required for ultimate display of "wire" obstacle information. The small size of wire obstacles requires accurate high resolution sensors. Consideration is therefore limited to lasers.

Operational Considerations

Many studies have been conducted to determine optimum terrain clearance techniques and equipment mechanizations. Most notable of these studies is the work conducted by Cornell Aeronautical Laboratories (CAL) on Advance Concepts for Terrain Avoidance (ADCON). These studies have been concerned with analyses of methods for enabling a penetrating aircraft to fly sufficiently low so that exposure to enemy air defenses is minimized. Emphasis has been placed on techniques suitable for flying at a minimum altitude while following the vertical contour of the terrain. Some effort has been given to a study of azimuth coverage necessary for turning flight to avoid obstacles. The aircraft velocities considered have generally been in the region of Mach 0.5 to 0.9. Relatively little work has been done to study terrain and obstacle avoidance requirements for helicopters.

The characteristics of the helicopter that make it very vulnerable to enemy fire of all types are its slow speed (220 knots maximum for future helicopters), large vulnerable area, and relatively low degree of protection provided for crew and installed equipment. In order to improve survivability and achieve surprise for attack, the helicopter crew performs nap-of-the-earth or contour flying whenever the possibility of enemy observation or fire exists. Nap-of-the-earth is defined as any route that affords cover for the helicopter. Such flight generally occurs at very low altitudes (0 to 30 feet)

and can include flight up valleys and among or behind trees. Because flights are frequently at extremely low altitudes, many man-made structures such as bridges, towers, and power lines are threats to safe flight. A more important category of safety threat is obstacles that an enemy can deliberately place in the path of aircraft to deny low-level flight along a specific route. These obstacles will probably consist mainly of horizontal wires or ropes strung between hills or trees but may also include vertical members suspended, for example, from balloons. In addition to the deliberate placement of such "wire" obstacles by a hostile force, there is the very real problem of casual wires that are a serious hazard in a completely friendly environment.

The unique performance characteristics of helicopters allow sensed obstacle data to be utilized in a different manner from that for fixed-wing aircraft. Helicopter speeds in the 1975 era may range from 0 to 220 knots, with most flying being done in the range of 100 to 140 knots. Allowable bank angles up to 60 degrees will provide very high turning rates. The combination of high allowable turning rates, and the desire to use nap-of-the-earth tactics may require considerable azimuth scan coverage.

The conditions under which the helicopter is used will range from daytime visual to night/all-weather. For daytime use it is unlikely that equipment can be designed to provide closer terrain clearance than is possible by manual flight. However, detection equipment will be required even under the best visual conditions to detect wire or cable type obstacles. These appear to pose the most serious threat to the low flying helicopter.

For night or all-weather use, the helicopter will be able to fly safely at slightly higher altitudes and the problem of terrain clearance more closely resembles that studied for the conventional tactical fighter. In this case, the studies, experiments, and simulations which have been conducted by Cornell Aeronautical Laboratories are directly applicable.

System Requirements

System requirements arise primarily from consideration of the types of obstacles encountered and the tactics employed to avoid them. On detection of an obstacle along the aircraft flight path, two choices of action

are available: the aircraft may fly over or around the obstacle. The main factors affecting the choice are:

- Vertical and lateral aircraft or crew acceleration
- Aerodynamic and operator limits lags
- Critical dimension of obstacle
- Navigation/turn avoidance conflicts
- Enemy defenses/turn avoidance conflicts

The selected sensor must be capable of obtaining critical dimension data for the obstacle in sufficient time to enable a decision and safe minimum clearance avoidance action. The system requirements imposed by the above considerations remain to be determined.

Consider an aircraft performing a horizontal obstacle avoidance maneuver. The assumptions inherent in this example are:

- The obstacle is detected in sufficient time to make a maneuver decision and to perform the maneuver.
- The obstacle avoidance system can determine the target dimension.
- The aircraft makes two coordinated turns at 30-degree bank angle during the avoidance maneuver so that the resultant heading change is zero.

Based on these assumptions the required minimum slant range to the obstacle is approximately

$$R_{\min} = \frac{a_L}{2\theta} \left\{ \frac{V\theta}{a_L} + \sqrt{\left(\frac{V\theta}{a_L}\right)^2 + \frac{2V\theta}{a_L}(t_D)} \right\}^2$$

where,

- R = slant range to obstacle
- a_L = aircraft lateral acceleration (0.5g)
- V = aircraft velocity (220 knots)
- θ = width of obstacle
- t_D = decision and reaction time (5.5 sec)

Example minimum range results, plotted as a function of aircraft velocity, are shown in Figure 66.

The obstacle clearance error (ΔC) is determined, in part, by the measurement errors in range and angle. The permissible range error, (ΔR) for a fixed acceptable obstacle clearance error, may be determined from the following equation:

$$\Delta R = \left[\frac{\Delta C^2 - \left\{ \left[-R \cos \psi + \frac{1}{4} a_L \frac{R^2 \sin 2\psi}{V^2} \right] \Delta \psi \right\}^2}{\left[\sin \psi - \frac{1}{2} a_L \frac{R \cos^2 \psi}{V^2} \right]} \right]^{1/2}$$

where ψ is the direction of the obstacle relative to the aircraft velocity vector and $\Delta \psi$ is the error in this measurement. Results are shown in Figure 67 as a plot of range error versus aircraft velocity for the conditions:

$$\begin{aligned} \psi &= 5 \text{ degrees} \\ \Delta \psi &= 4 \text{ milliradians} \\ \Delta C &= 25 \text{ feet} \end{aligned}$$

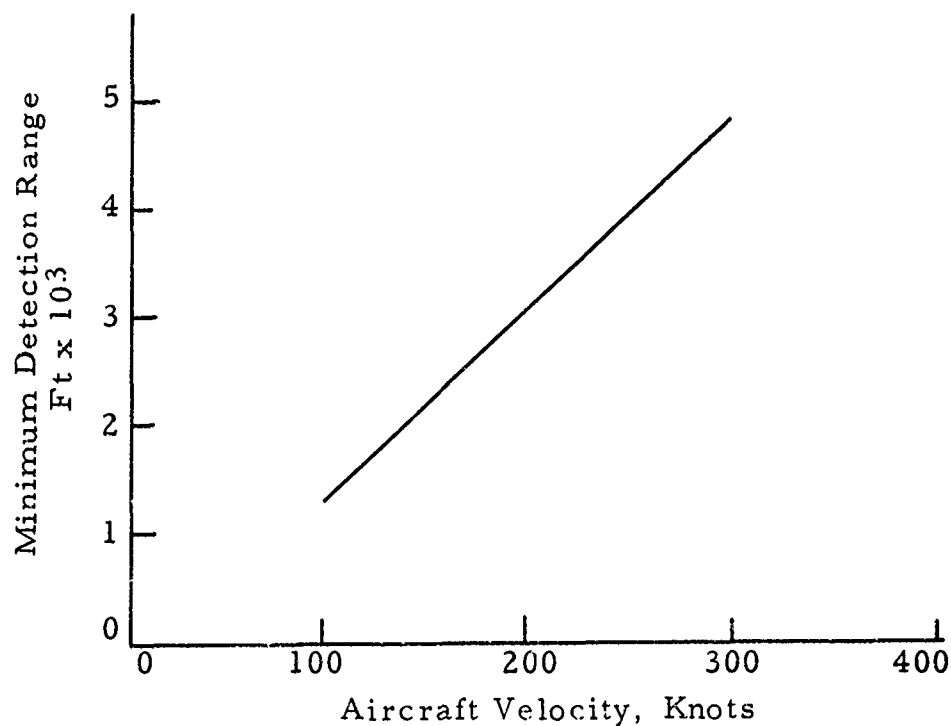


Figure 66. Allowable Range Error for 25-Foot Obstacle Clearance

The above results are illustrative only; it is necessary that future analyses of this general type be conducted to define the required sensor operating range and allowable measurement errors. Subsequent sensor studies and tests can then be compared with these requirements. These studies should include consideration of both vertical and horizontal avoidance techniques against various types of obstacles.

The beam coverage envisioned for the takeoff and landing phases is different than that for cruise. For these relatively short-range and low-speed phases the search angle should be about 30 degrees and the maximum cutoff range need only be about 400 feet. The scan pattern should provide high probability of detecting any 5-foot vertical rod within 50 feet of the intended touch down spot. Wires 5 feet or more above the terrain background should be detectable at near maximum range.

During the cruise phase the minimum warning range should allow two seconds for pilot reaction plus an additional three seconds for the helicopter to clear a 100-foot obstacle, or otherwise avoid it. The laser beam must sweep out a 100-foot diameter safe passage way at this minimum warning range. There should also be a maximum cutoff range and a range at which an isolated wire can be detected against a difficult background. The laser device should be able to detect reliably any wire-like obstacle which is 10 percent closer than the background (or 10 feet closer, whichever is greater).

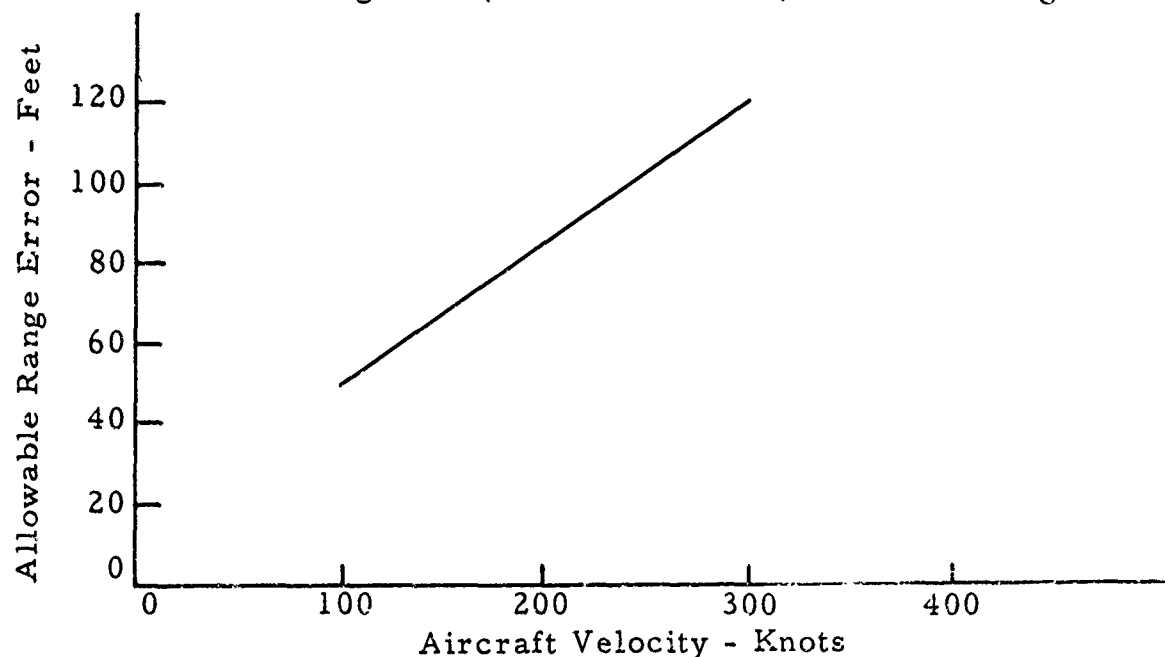


Figure 67. Allowable Range Error for 25-foot Obstacle Clearance Error

Laser Obstacle Detection Considerations

Although laser frequencies will not provide all-weather obstacle detection, the high frequency does offer potential for detection of small targets under visual conditions. Furthermore, since lasers will be included on many helicopters in the future, their inherent obstacle detection capabilities should be investigated.

The system constraints on laser design can be most easily understood by referring to the fundamental range equation for the case where only a portion of the transmitted beam intercepts the obstacle. This would be the case for obstacles narrow in one dimension such as a wire. The range equation may be written as

$$N_s = E_\ell \frac{\eta_q}{h\nu} \cdot \frac{K A_T A_r}{\Omega_t R^4} \cdot T^2 \eta_t \eta_r$$

where

N_s = number of signal photoelectrons required for detection

E_ℓ = laser pulse energy, joules

η_q = detector quantum efficiency

h = Planck's constant

ν = laser frequency

K = effective target reflectance

A_T = area of target illuminated

A_r = area of receiver aperture

T = atmospheric transmission

η_t = transmitter optical efficiency

η_r = receiver optical efficiency

Ω_t = transmitter beam solid angle, steradians

R = range

When rearranged as shown below, the left side of this equation represents those parameters specified by the system designer while those on the right represent parameters to be optimized in equipment design.

$$\frac{\Omega_t R^4}{K A_T A_r T^2} = \frac{E_l \eta_q \eta_t \eta_r}{h \nu N_s}$$

The optimum system for a given set of conditions must be found by appropriate tradeoffs. Thus the beam width should be sufficiently wide to ensure interception of the obstacle but must be traded off against required detection range, as well as other parameters, so that the state of the art (represented by the terms on right side) is not exceeded.

The beam shape and method of scanning must be optimized with reference to obstacle detection and comprehension of features as required to determine appropriate evasive maneuvers. Target reflectivity and configuration are fundamental to this study.

The aperture diameter is constrained by aircraft installation considerations. Since the receiver aperture is closely related to the required laser energy, a tradeoff must be conducted.

Atmospheric transmission is a function of range as indicated by the equation

$$T = e^{-(\alpha + \beta) R}$$

where α and β are the atmospheric absorption and scattering coefficients, respectively. Because these are both a function of wavelength, atmospheric conditions will enter into the selection of laser operating frequency.

System weight does not appear explicitly in the range equation. However, it is a function of laser energy and receiver aperture and thus should be traded off against other variables.

Tradeoffs within the equipment design area must include the selection of a laser as a function of operating wavelength with reference to atmospheric transmission, efficiency of optics, and particularly to detector efficiencies. Photomultiplier detectors have low quantum efficiencies but compensate for this by providing noise-free gain at the input. Solid-state detectors, conversely, have high quantum efficiencies, but in general provide no gain. The choice of detector, then, depends not only on frequency but on the source and level of the limiting noise.

Laser Signal Detection

Although separated by more than three orders of magnitude in the spectrum, the basic process for detection of obstacles remains the same at laser wavelengths as for millimeter wavelengths. There are, however, differences in the detection mechanization.

The mechanism for generating electromagnetic radiation at visible and infrared frequencies, for example, is based on atomic and molecular energy levels, involving bound rather than free electrons and is at present almost two orders of magnitude less efficient than millimeter-wave generation. Thus, while in principle the shorter wavelengths may permit a more compact transmitter, the higher energy density may prevent realization of this advantage.

At wavelengths of a micron or less, a transmitting aperture 1 cm in diameter is adequate to define the beam, in the diffraction limit, to about 0.1 milliradian. On the other hand, the requirement that the receiving aperture be as large as practical for maximal collection of returned energy remains unchanged.

Atmospheric transmission generally is reduced at laser wavelengths, since scattering increases as wavelength approaches molecular or particle dimensions, and may be highly dependent on wavelength due to absorption lines. Target reflectance, whether diffuse or specular, and effective target cross section are more sensitive to surface conditions than at longer wavelengths. These effects, which can be assessed qualitatively from our

own visual experience of objects under illumination by headlights or spotlights, have been the subject of only preliminary studies to date and require much further investigation in order to obtain quantitative data needed for valid systems analyses.

Photon detectors are by their nature square law detectors inasmuch as output current is proportional to input power. For this reason, incoherent signal detection in the presence of noise is a function of peak power (for a given signal energy) and leads to the conclusion that an appropriate system might utilize a giant-pulse laser operating at as high a peak power and as low a repetition rate as allowed by available power and required data rate. An optical pulse compression technique might be used to enhance further the effective peak power. Another approach, however, makes use of signal coherence; optical heterodyning provides a mechanism for raising a signal out of a noise background so that detection approaches dependence on signal statistics alone. Under these conditions, detection depends just on signal energy received, thus permitting the effective use of CW lasers for detection. The various approaches to improved signal detection require further study so that valid tradeoffs can be made.

Eye Damage Considerations

It seems evident that to take advantage of the laser's easily achieved narrow beam widths and short pulses to perform a 3-dimensional discrimination in range and angular direction between wires and (say) ground, a scanning technique must be used. If this discrimination is to be fine grained enough to be of operational utility, a very high repetition rate, ultra short pulse laser source of sufficient power is required. Further, the wavelength should be one where very sensitive detectors are available to minimize required transmitted power and in this way to minimize the eye damage potential of the system. This has not been possible with conventional Q-switched solid state lasers. It is only recently that advances in the laser state of art has given promise of a source which will meet these requirements.

The argon ion laser operates in the blue-green region of the spectrum where detector sensitivity is substantially greater than at ruby wavelengths and several orders of magnitude greater than at the neodymium ion wavelength (in a glass, calcium tungstate, or YAG host). This laser can be operated in a pulsed manner by modulating the input. Our analysis indicates that the laser requirements of the system at the argon ion emission wavelengths (in the blue-green) are: 10 nanosecond pulses of 100 watts power at a PRF of 10,000 per second. This corresponds to a microjoule per pulse or only 10 milliwatts average output power. In addition, reasonable dimensions are necessary and an efficiency of 5×10^{-5} or better is required to stay within readily available power capacity.

The state of the art in argon ion lasers approximately a year ago was characterized by pulsed operation of the required pulse length and peak power, but with an efficiency of the order of 1 or 2×10^{-5} in a rather oversized tube. Steady, swift progress in use of new electrode techniques and magnetic confinement have resulted in compact argon ion CW units with efficiencies of the order of 10^{-3} and with average output power approximately 2 orders of magnitude higher than required. We believe that with sufficient effort these advances in CW operation can be transposed to short pulse operation. Another candidate, though less attractive from the viewpoint of detector efficiency, is the pulsed Neon laser. This, too, should be examined. Future advances in the detector state of art could possibly make semiconductor injection lasers of interest.

A previous analysis (see Figure 66) shows a detection range of 1000 feet is suitable for a slowly moving (about 80 knots) helicopter. If we use this detection range with a 10 milliwatt average power laser having 12 cm optics the resulting energy density is approximately equal to 10^{-8} joules/cm² for no beam spread. This amount is equivalent to that to which we estimate some of our laboratory personnel are exposed. These people have shown no evidence of retinal damage after several years of periodic examinations by medical experts from UCLA. In the case of a dark adapted eye, this energy per pulse is slightly greater than the 10^{-9} joule at the iris recommended as

safe by the office of the Surgeon General. However, in the case of a day-light adapted eye, the energy even meets this more stringent safety requirement.

Experimental measurements indicate that for damage to rabbit retinas the threshold energy density is both a function of time and retinal area as shown in Figure 68. The correspondence for rabbit and human retinas under conditions of high intensity levels such as occur with laser energy sources has been substantiated by Weale (1964). Of particular interest to the system suggested here are measurements reported at the Washington Laser Conference on Biological Effects (sponsored by the Army Surgeon General's Office) by William Ham, who reported a threshold at the retina of 0.07 joule/cm^2 for a Q-switched ruby laser pulse of about 25 nanoseconds duration. The diameter of the spot in his experiments was of the order of 1 millimeter; since the threshold is found to be an inverse function of the spot size, it will be conservative to use this value for smaller spot sizes

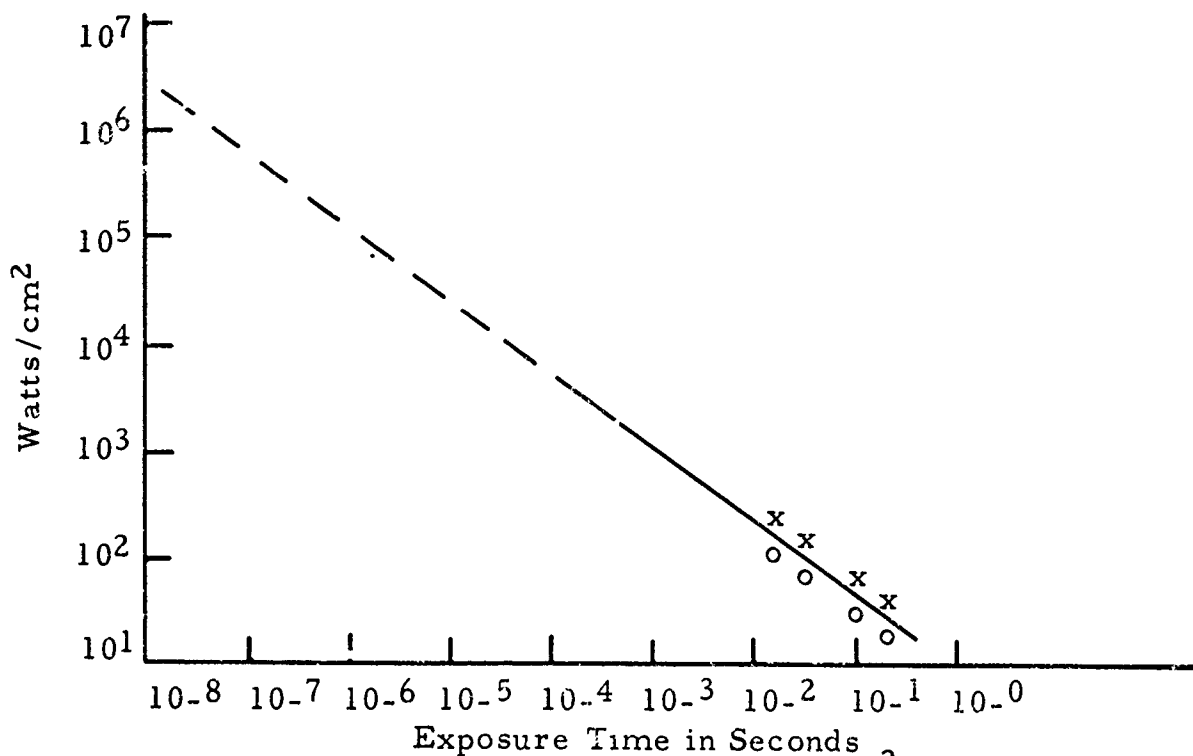


Figure 68. Log-log plot of power density in watts/cm² versus exposure time in seconds for the production of very mild lesions in the rabbit retina. The straight line represents data for retinal image diameters of 0.8 mm. Some data points for image diameters of 1.0 mm (circles) and 0.54 (crosses) are plotted for the longer exposure times. The data point at the extrapolated end of the curve represents a Q-switched pulse.

such as will normally occur due to the focussing action of the eye. Based on this value, the damage threshold will be reached at a level of 2×10^{-7} joule/cm² at the entrance pupil of the normal, light-adapted human eye, where it is assumed that the light is focussed down to the diffraction limit at the retina. For a dark adapted eye more light will be admitted by the dilation of the pupil with the possibility of its being concentrated in an even smaller spot. (The spot size is unlikely to reduce by much in practice, however, due to the reduced depth of focus.) Since the threshold increases with reduced spot size, and since the maximum dilation of the pupil represents one order of magnitude in area, we can expect that an energy density of 10^{-8} joule/cm² will be below the damage threshold under both day and night conditions.

VELOCITY VECTOR SENSING

General

In the VSI displays the incorporation of a velocity vector symbol was suggested in order to inform the pilot of the velocity vector with respect to the ground. The information to drive the symbol does not exist in appropriate form in current systems and a requirement therefore exists to determine how this information may be sensed or derived through processing.

The determination of the velocity vector in space involves sensing three quantities. There is some choice in selecting quantities that make up the velocity vector. One choice is the combination of the magnitude of the vector plus two angles which define the spatial rotation of the speed scalar. Another choice is the combination of three orthogonal components of velocity.

Various equipments exist for sensing the above quantities. An inertial platform senses three orthogonal accelerations and when each output is integrated once yields three orthogonal velocities. A doppler navigation radar yields either three velocity components or horizontal velocity vertical velocity, and drift angle.

The ranges of each type of equipment makes either or both suited to both types of aircraft being considered. However, the need for rather precise alignment techniques makes an inertial platform impractical for a helicopter operating in a primitive environment.

Accuracy

It is necessary to examine the accuracy obtainable with this equipment. For the inertial platform we will consider a simplified velocity error propagation. This is done by differentiating position error equations which is not an absolutely rigorously correct procedure but does include all first-order effects. This main source of error and the corresponding velocity error expressions are given in Table XVIII.

Table XVIII.

Error Source	Velocity Error
Accelerometer Bias (B)	$\frac{B}{\omega_o} \sin \omega_o t$
Platform tilt ($\phi_y(0)$)	$R_o \omega_o \phi_y(0) \sin \omega_o t$
Accelerometer Scale Factor Error (K)	$K \Delta V_y \cos \omega_o t$ $\Delta V_y = \text{change in velocity}$
Gyro Drift (ϵ_y)	$R_o \epsilon_y (\cos \omega_o t - 1)$
Initial Velocity error ($\Delta \dot{x}(0)$)	$-\Delta \dot{x}(0) \cos \omega_o t$
Initial Azimuth Error ($\phi_z(0)$)	$\phi_z(0) R_o \omega_x (\cos \omega_o t - 1)$

Using the error source values below, the overall rms velocity error is just under 1 ft/sec (0.96 ft/sec)

$$B = 5 \times 10^{-5}$$

$$\omega_o = 1/800 \text{ rad}$$

$$\phi_y(0) = 5 \text{ secs}$$

$$K = 10^{-3}$$

$$\epsilon_x = 0.001^\circ/\text{hr}$$

$$R_o = 2.09 \times 10^7 \text{ ft}$$

$$\Delta_x(0) = 0.5 \text{ ft/sec}$$

$$\phi_z(0) = 100 \text{ sec}$$

$$V_x = R_o \omega_x = 1000 \text{ ft/sec}$$

$$\Delta V_x = 100 \text{ ft/sec}$$

Similar values exist in each of three orthogonal channels and thus the angular accuracies can be calculated for any given set of velocities and the associated errors.

To a first approximation for small vertical velocity and small drift angles

$$\Delta\theta = \frac{\Delta V_z}{\sqrt{V_x^2 + V_y^2}}$$

and

$$\Delta\delta = \frac{\Delta V_y}{V_x}$$

For

$$V_x = 1000 \text{ ft/sec}$$

and

$$\Delta V_y = \Delta V_z = 1 \text{ ft/sec}$$

$$V_y = 50 \text{ ft/sec}$$

$$\Delta \theta = 10^{-3} \text{ rad}$$

$$\Delta \delta = 10^{-3} \text{ rad}$$

For

$$V_x = 200 \text{ ft/sec}$$

$$\Delta \theta = 5 \times 10^{-3} \text{ rad}$$

The error in the magnitude of the velocity vector is:

$$\Delta V = \sqrt{\Delta V_x^2 + \Delta V_y^2 + \Delta V_z^2} = \sqrt{3} \text{ ft/sec}$$

for 1 ft/sec errors in each channel.

Thus, the angular errors are a function of velocity while the magnitude error is not.

The errors obtained with a typical doppler navigation system are:

$$\Delta V_x = \pm 0.2\% \quad V_x \pm 0.2 \text{ knots}$$

$$\Delta V_y = \pm 0.2\% \quad V_y \pm 0.2 \text{ knots}$$

$$\Delta V_z = 0.5\% \quad V_z \pm 0.25 \text{ knots}$$

For

$$V_x = 1000 \text{ ft/sec}$$

$$\Delta \theta = 2 \times 10^{-3} \text{ radians}$$

$$\Delta \delta = 2 \times 10^{-3} \text{ radians}$$

For

$$V = 200 \text{ ft/sec}$$

$$\Delta\theta = 2.25 \times 10^{-3} \text{ radians}$$

$$\Delta\delta = 2.5 \times 10^{-3} \text{ radians}$$

The error in the magnitude of the velocity is

$$\Delta V = 0.35 \pm 0.2\% V_x \pm 0.2\% V_y \pm 0.5\% V_z$$

In this case the angular errors are practically constant with varying velocity but the magnitude error depends on velocity. The display of the velocity vector is confined to positioning a symbol in azimuth and elevation. The elevation and azimuth angles are found from the following expressions:

$$\theta = \tan^{-1} \frac{V_z}{\sqrt{V_x^2 + V_y^2}} + \theta_o$$

$$\delta = \tan^{-1} \frac{V_y}{V_x} + \delta_o$$

Future Investigations

An area for further investigation remains. There exists a tradeoff between lag and signal smoothing in both the doppler and inertial equipments.

In the case of the doppler equipment a one-half to one second smoothing time constant is purposely incorporated. This results in an unacceptable lag for displaying a landing dot which is to be flown.

Theoretically an inertial system should have a fast response (one or two milliseconds). However, it has been found that due to non-rigid mounting this is not the case. It is not known whether a more rigid mounting might result in unacceptable noise levels to plague the system.

It becomes important to gather data to resolve the above.

An additional avenue of investigation presents itself when the idea of using this information (the velocity vector) to aid in landing aircraft on carriers is considered. The basic accuracy of the information and the possibility of incorporating the complex carrier deck motions into a command vector appropriately displayed should be investigated. This coupled with radar could provide an all-weather landing capability.

DETERMINATION OF COMMAND VELOCITY VECTOR

On the VSD skeletal display a symbol representing the command velocity vector was suggested. Similarly, the flight path in the contact analog display, if used as a command flight path, requires the calculation of the command velocity vector to provide inputs to the flight path display generator. As was stated in earlier sections of this report the calculation of the command velocity vector for the mission phases considered can be conveniently analyzed only in the vertical plane. The derivation of optimum turning maneuvers escapes formal analysis and in a real system the plan position and heading of the flight path will be crew selected except in those cases where the information is derived from an external source. Optimum profiles in the vertical plane, however, are susceptible to analysis and the following paragraphs suggest a method whereby this may be done.

As an integral part of the MA-1 Fire Control System for the F-106, flight paths were developed by ground-based computation, stored in the memory of the airborne computer and flown by the aircraft. In this manner, optimized speed-altitude scheduling was incorporated within the climb, cruise and descent phases of flight. The techniques employed in generating the initial profiles have been modified and extended for application to a wider band of vehicles. Efforts in relation to the F-106, F-108 and two versions of NASA supersonic transport configurations have resulted in successively updating the computer program which simulates the flight and produces the required optimum flight path. As a result, a tool has evolved which is applicable for performance analysis and optimization determination for a variety of aircraft. Speed-altitude schedules which optimize aircraft performance with respect to several parameters are obtainable using the computer program, operational on the IBM 7094 Data Processor. Therefore, it is possible to minimize fuel or time and to maximize specific range by using the simulation.

The computer flight simulation program is applicable to any aircraft for which the aerodynamic variables are defined. The information required to simulate a particular aircraft's mission is a complete definition of the

aircraft's lift and drag characteristics, as well as the aircraft's powerplant performance parameters, such as inlet drag and recovery, thrust and fuel flow. The only possible restriction or limitation to the simulation program in its present form is that climbs must be performed with a constant throttle setting and descents must be performed at idle thrust. Also, the simulated missions of the program are in the Mach-altitude-range plane. Lateral turning effects on aircraft performance are considered during holding and loiter patterns, but the flight path track during these maneuvers is imaginary, i. e., the aircraft change in azimuth is not recorded.

Several factors were found to influence the selection of the optimum flight path in climb and descent for supersonic transport aircraft, which need to be considered in computing an optimum flight path for other aircraft types. Two are aircraft weight and atmospheric conditions. At one particular aircraft weight and one atmospheric condition, a certain optimum profile exists (either minimum time, minimum fuel or maximum specific range) in the Mach-altitude range plane. A change in either aircraft weight or atmospheric condition will cause a change in the predicted optimum profile. The extent of this change in profile is dependent upon the type of aircraft (i. e., the possible percent weight deviation) and the magnitude and the position relative to the optimum profile of the atmospheric change.

Method

In order to present to the pilot of an aircraft a display which commands a particular flight profile, certain inputs are necessary to drive the display system. For the contact analog type of display system the command inputs required (provided motion in only the Mach-altitude-range plane is considered) are:

- 1) pitch angle
- 2) flight path angle
- 3) altitude
- 4) horizontal velocity
- 5) vertical velocity

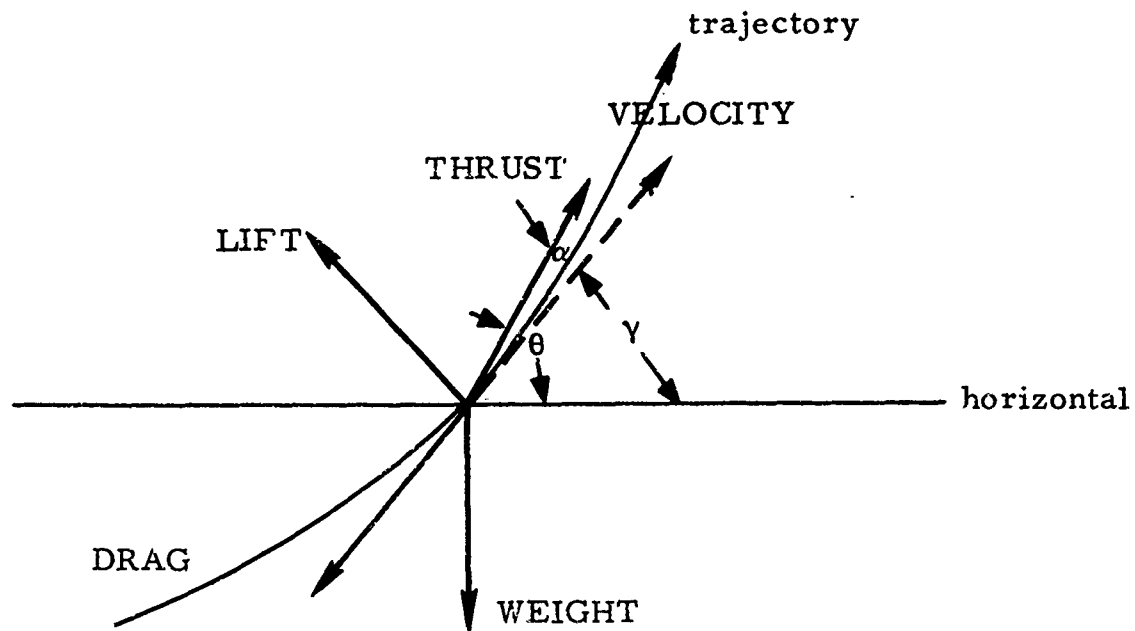
- 6) aircraft airspeed
- 7) errors that exist between the above command parameters and the actual aircraft values.

The above inputs must be supplied to the display system for a particular flight path if that flight path is to be commanded. Inputs 1 through 6 are measured parameters that define the actual position of the aircraft (in the Mach-altitude-range plane) and input 7 gives the error between the actual aircraft position and the desired position as obtained from pre-stored profile information. When the aircraft is on the desired profile, the display system must indicate to the pilot what flight path changes are necessary in the immediate future in order for the desired profile to be maintained. Should the aircraft be off the desired profile the system must sense this and command a display which will indicate the return path to the desired profile.

The simulation program considers the aircraft as a dynamic body. The equations used in developing the optimum profiles are equations of dynamic motion obtained by the free body technique with certain restraints necessary for the dynamic programming method of solution. Figure 69 shows the free body diagram and the dynamic equations. As can be seen by the simulation equations, the parameters pertinent to a command display system exist and they can be provided by the program output. For any particular flight profile these parameters can be generated by the ground-based computer simulation. It then becomes necessary to store these parameters on board the aircraft as a part of the airborne profile control law program. This airborne program would then not only command a Mach-altitude profile, as in the F-106 MA-1 system, but would also provide the pilot with a visual command of the desired profile.

For any particular aircraft, implementation of this command profile display system requires study in four areas:

- 1) Determination of optimum profiles.
- 2) Effect of weight, configuration and atmosphere on optimum profiles.



Solving for Σ Forces Vertical and Horizontal

$$\dot{V} = \frac{T}{m} \cos \alpha - \frac{D}{m} - g \sin \gamma$$

$$\dot{\gamma} = 0 = \frac{L}{mV} + \frac{T}{mV} \sin \alpha - \frac{g}{V} \cos \gamma$$

where:

V = velocity

T = thrust

L = lift

D = drag

m = Weight/gravity constant - W/g

α = angle of attack

γ = flight path angle

$\dot{\gamma} = 0$ because no accelerating maneuvers are considered

θ = pitch angle = $\alpha + \gamma$

Figure 69. Free Body Diagram and Equations

- 3) Simplification of optimum profiles for minimum computer storage space.
- 4) Development of the control laws which dictate how the aircraft shall reach the optimum profile from a non-optimum condition.

In the second area of study listed above, the purpose is to determine how much deviation from a standard optimum profile is possible and whether an interpolation scheme is feasible for between-profile-conditions. A minimum number of profiles to be stored is desirable in order to keep program storage low.

The third area of study is for the purpose of simplifying the form in which a profile is stored. It is possible that the various command parameters can be stored as mathematical functions, rather than in tabular form.

The fourth area of study would be to determine what is the best manner with which to bring the aircraft to an optimum profile from a position which is not on the desired optimum profile. Included in this study would be the command display functions necessary to indicate to the pilot how to reach the optimum.

For a "skeletal" version of the VSD display, that is, the display of the velocity vector of the aircraft and the command vector rather than the command flight path, the output and computing requirements of the display system are reduced. The system does not have to construct the command "pathway" but, instead, displays the command velocity vector on a real time basis.

A schematic of the command display system is shown in Figure 70. The pilot control panel shown may be a keyboard type whereby the pilot can input the aircraft configuration, weight and atmospheric data (if necessary). Also, if climbing or descending, the end point Mach and altitude can be input or a cruise control mode may be selected. Once the desired maneuver has been selected by the pilot, the airborne program will determine the profile to be followed (by interpolation of the stored profiles if necessary) and display this profile as a visual command to the pilot. If it is sensed that the

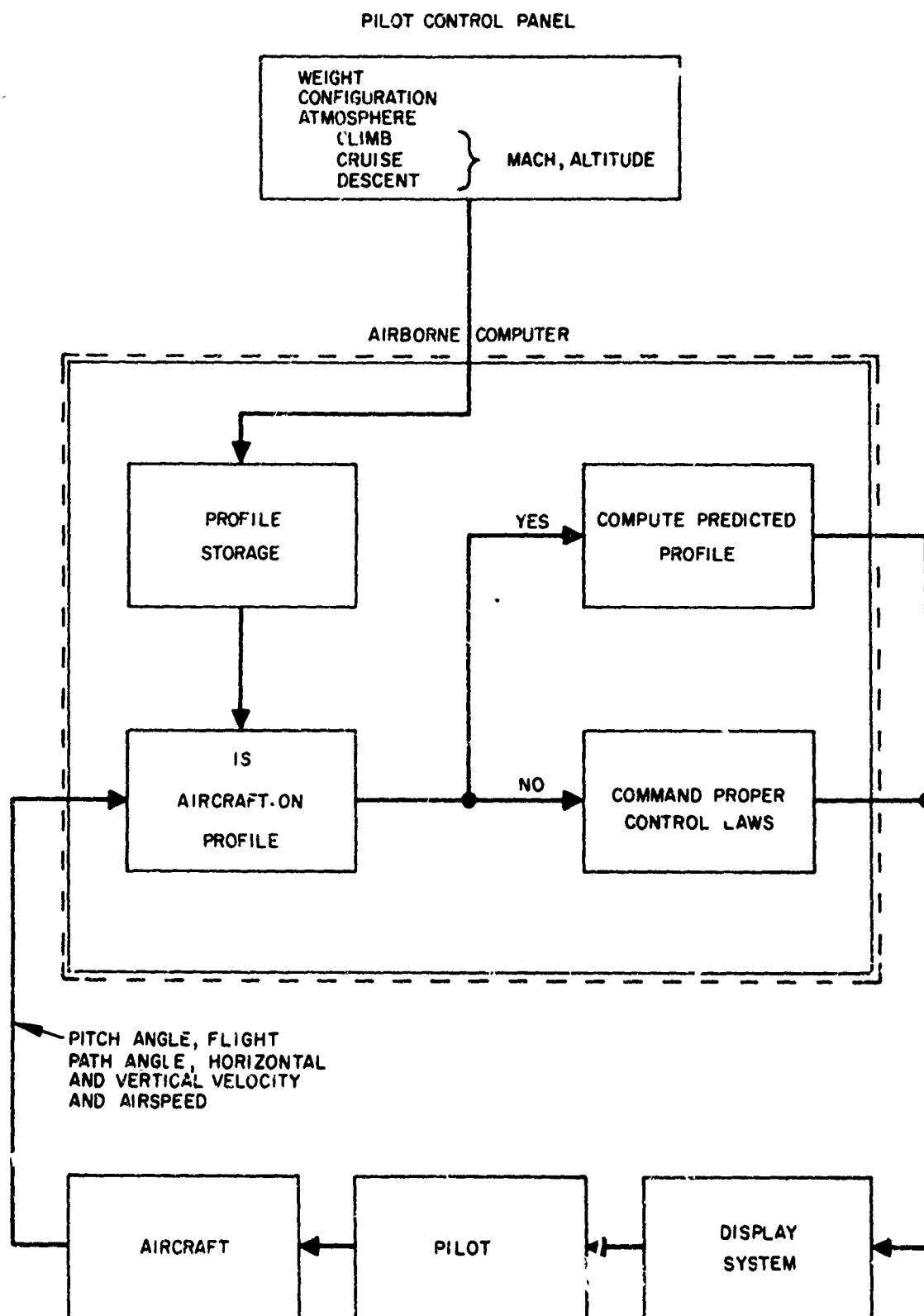


Figure 70. Program Schematic

aircraft is not on the desired profile, the program will select the control law necessary to return to the profile and display this projected maneuver to the pilot.

It was noted earlier that certain command inputs are required to drive a contact analog type of display. One input is the error that exists between the actual aircraft position and the desired profile (input number 7). This type of input implies that there are means of determining by measurement onboard the aircraft the inputs of numbers 1 through 6. If it can be assumed that an inertial navigation system is onboard the aircraft, these inputs are readily available. The accuracy of these parameters from an inertial navigation system are probably adequate for the command display system, but verification of this fact should be made. Without an inertial navigation system some method of physically measuring pitch angle and angle of attack must exist in order to determine the flight path angle (Figure 1). However, inaccuracies associated with angle of attack and pitch angle measurement may preclude this method of approach. Also, without an inertial navigation system, the aircraft ground speed cannot be determined, and this factor may be an important consideration when displaying the horizontal ground motion to the pilot due to the fact that the difference between airspeed and ground speed becomes more significant at lower altitudes (i. e., during landing). However, aircraft ground speed may be available from some other source such as a doppler system.

A flight path command display system may also be utilized as a predicted flight path display system. Assuming that the necessary inputs have been measured (inputs 1 through 6 and their derivatives), the flight path can be projected ahead for some finite time period and displayed to the pilot. This is accomplished by integrating the dynamic parameters and their derivatives in the Mach-altitude-range plane over a given time period. The time period in which the flight path can be projected would have to be determined through a sensitivity study of the associated inputs. Possibly a simulation could be performed to evaluate the flight path prediction system

by simulating a particular established profile and comparing the predicted flight path to the command path for that profile.

Conclusions

Existing ground-based computer flight simulation programs can be utilized to generate the input parameters required for a contact analog command display system. Additional study is required to determine how this generated information can be stored and utilized onboard a particular aircraft. The amount of information to be stored and the form with which it can be stored will depend in part upon the type of aircraft. The measurement of the pertinent parameters in order to determine the aircraft's position relative to the command profile is dependent upon the systems which are either already onboard the aircraft or can be provided. The relative accuracy of the measuring systems and its affect on the display system should be important criteria in considering where to obtain a measurement.

Once the pertinent measurements have been obtained it becomes a dynamic problem to project the flight path of the aircraft ahead for a given finite period of time.

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13. ABSTRACT This report contains a rationale for the use of Pictorial Displays. Summary evaluations of current or proposed Pictorial Flight Displays are included. The emphasis is on Raster Scan Display Media and such media are discussed. Sensor and data processing requirements are analyzed. Flight displays, navigation displays, and target recognition displays are discussed.

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